Sustainable and intelligent management of energy for smarter railway systems in Europe: an integrated optimization approach

D1.1 Railway network key elements and main sub-systems specification

Due date of deliverable: 31/05/2013
Actual submission date: 03/12/2013

Leader of this Deliverable: Emilio Facchinetti – Ansaldo STS
Reviewed: Y

<table>
<thead>
<tr>
<th>Document status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revision</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

Project co-funded by the European Commission within the Seven Framework Programme (2007-2013)

<table>
<thead>
<tr>
<th>Dissemination Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU</td>
</tr>
<tr>
<td>PP</td>
</tr>
<tr>
<td>RE</td>
</tr>
<tr>
<td>CO</td>
</tr>
</tbody>
</table>

Start date of project: 01/10/2012
Duration: 36 months
EXECUTIVE SUMMARY

The main aim of this document is to provide a general description and characterization of a generic mainline railway system.

An electrified railway system is complex distributed engineering system and can be described as a closely-knitted integration of a number of sub-systems which interact continuously with each other influencing the global energy consumption. In this document the structure of a generic railway networks is described through the definition of its sub-systems and main components. Furthermore the document reports an overview on the state of the art of the main technological solutions (such as reversible sub-stations or energy storage systems) that are now increasingly used to reduce the global system’s energy consumption in modern railway networks. Finally, the document covers the description of main railway system’s non-electrical constraints, related to legislation, energy supply and consumption contractual commitments, and possible control procedures.

Several set of category could be identified for the classification of the railway networks sub-systems. For the aim of this document, a first layer of railway subsystem classification is defined with respect to their physical position within the railway system, distinguishing between fixed and vehicle on-board sub-systems. Afterwards, fixed and on-board sub-systems are further classified on the basis of the function they perform; three main classes are identified:

1. **Traction power related and power supply system**
   Consisting of those sub-systems relevant to the energy and power supplying and feeding functionalities, including the interface with external power network, the traction power sub-system and the traction line sub-system.

2. **Operational related system**
   Mainly referred to communication and data transmission, control and diagnostic architecture, signalling subsystems.

3. **Auxiliary system**
   Including those sub-systems that do not concern directly to train operation and traction loads or power supply (e.g. HVAC sub-system or non-traction power supply sub-system).

In order to provide an overall description of a generic railway system, the document also includes the definition and the description of some technological solutions widely implemented in modern electrified transit systems to improve the global system’s energy efficiency. In particular the document covers some aspects relevant to the use of regenerating braking functionality, reversible traction power supply substations (both for DC and AC power supplied systems), energy storage systems (both mechanical and electrical or electrochemical systems) and the exploitation of renewable local energy sources (e.g. photovoltaic panels or wind generators).

Finally, the document reports an assessment on railway system’s interfaces affecting the global energy consumption and management. Specifically, an overview on system’s non-electrical internal and external constraints is reported. These would include topics relevant to legislation (e.g. TSIs or directives), energy supply and consumption contractual commitments, and possible control procedures. Two main layers for the analysis are identified: the first one concerns the legal constraints and includes the identification of standards and legislation generally set to the relationship between railway systems and energy suppliers’ infrastructures. It represents the legal
framework for the railway system. The second analysis’ layer concerns the contractual relationship between energy suppliers and railway systems, including the definition of real practice and procedures. When possible, the analysis is performed on a per-country basis, referring to three main scenarios reflecting the legal and contractual commitment usual context in Spain, United Kingdom and Sweden. These scenarios were built referring to the information provided by different consortium project members, infrastructure managers or operators involved in the project.
TABLE OF CONTENTS

Executive Summary ........................................................................................................... 2
List of Figures ......................................................................................................................... 8
List of Tables .......................................................................................................................... 10
List of acronyms ...................................................................................................................... 11
1. Introduction ......................................................................................................................... 18
   1.1 The MERLIN project ....................................................................................................... 18
   1.2 The RailEnergy project experience .................................................................................. 19
      1.2.1 The interface of RailEnergy and MERLIN ............................................................... 19
      1.2.2 RailEnergy outcome ................................................................................................. 20
      1.2.3 RailEnergy references ............................................................................................. 22
2. The Railway System ........................................................................................................... 24
   2.1 Fixed facilities, infrastructures and wayside related subsystems ......................................... 25
      2.1.1 Traction power related and power supply systems ................................................... 25
      2.1.2 Operational related systems ..................................................................................... 43
      2.1.3 Auxiliary systems ...................................................................................................... 53
      2.1.4 Reference documents and standards for fixed facilities and infrastructures ............. 63
   2.2 Rolling stock subsystems ................................................................................................. 66
      2.2.1 Traction power related and power supply systems ................................................... 66
      2.2.2 Operational related systems ..................................................................................... 83
      2.2.3 Auxiliary systems ..................................................................................................... 87
      2.2.4 Referenced documents and standards for rolling stocks .......................................... 94
3. Technology solution for railway systems ............................................................................. 96
   3.1 Reversible Traction substations ....................................................................................... 96
      3.1.1 Reversible electric substation and controllable power conversion equipment for DC traction networks ........................................................................................................ 97
      3.1.2 Reversible frequency converters for 15 kV 16.67 Hz traction systems ..................... 99
   3.2 Energy storage systems ................................................................................................. 105
      3.2.1 Mechanical energy storage systems .......................................................................... 106
      3.2.2 Electric and electrochemical ESS ............................................................................ 107
   3.3 Local energy sources ...................................................................................................... 110
      3.3.1 Photovoltaic panels .................................................................................................. 110
      3.3.2 Wind generators ....................................................................................................... 111
4. Non-electrical constraints and interfaces, legislation, procedures ......................................... 113
   4.1 Legal constraints ............................................................................................................. 114
4.1.1 European Directives .............................................................................. 114
4.1.2 European Decisions ............................................................................. 115
4.1.3 European Studies and Standards ............................................................ 116
4.1.4 National Standards ................................................................................ 117

4.2 Contractual relationship between energy suppliers and railways ................... 119
4.2.1 Billing payment criteria, procedures/frameworks for energy provision to railways 119
4.2.2 Kind/level of standardization for the energy meters .................................. 123
4.2.3 Main present issues/problems related with standardization/calibration of energy meters and data communication .................................................. 124
4.2.4 Energy flow back from the railways network to the external power network ... 127
4.2.5 Possible technologies for energy storage/regeneration (used or planned to be introduced) ............................................................ 128

Appendix .............................................................................................................. 131
1. Railenergy’s KPIs ......................................................................................... 131
   1.1 Introduction .............................................................................................. 131
   1.2 KPI 1 - Final energy consumption per traction effort .................................. 131
   1.3 KPI 2 – Final energy consumption per offered transport .......................... 132
   1.4 KPI 3 – Primary energy consumption per actual traffic output (facultative) .... 132
   1.5 KPI 4 – Final energy consumption per actual traffic output ....................... 132
   1.6 KPI 5 – Share of energy consumption for parked trains ............................. 133
   1.7 KPI 6 – Energy recuperation rate ............................................................... 133
   1.8 KPI 7 – Efficiency of the railway distribution grid ....................................... 134
   1.9 Different applications of KPIs ................................................................. 134

2. Railenergy’s Verification, Evaluation and Assessment Process .......................... 134
   2.1 Introduction of RailEnergy’s Methodology .................................................. 134
   2.2 Verification, Evaluation and Assessment Process ........................................ 135
   2.3 Lessons Learned and Findings from Simulation, Verification, Evaluation and Assessment Process ............................................................... 136

3. Railenergy’s energy efficient Technologies ...................................................... 137
   3.1 Overview ................................................................................................... 137
   3.2 Energy efficient train operation (EETROP) ............................................... 137
      3.2.1 Technology description ....................................................................... 137
      3.2.2 Advantages of the new technology ...................................................... 138
   3.3 Reversible dc substation .......................................................................... 138
      3.3.1 Technology description ....................................................................... 138
      3.3.2 Advantages of the new technology ...................................................... 138
   3.4 Real time management .............................................................................. 138
3.4.1 Technology description ................................................................. 138
3.4.2 Advantages of the new technology .............................................. 138

3.5 2 x 1.5 kV dc traction system ......................................................... 139
3.5.1 Technology description ................................................................. 139
3.5.2 Advantages of the new technology .............................................. 139

3.6 Asymmetrical autotransformer system ........................................... 139
3.6.1 Technology description ................................................................. 139
3.6.2 Advantages of the new technology .............................................. 139

3.7 Parallel substation ............................................................................ 139
3.7.1 Technology description ................................................................. 139
3.7.2 Advantages of the new technology .............................................. 140

3.8 Increased line voltage ...................................................................... 140
3.8.1 Technology description ................................................................. 140
3.8.2 Advantages of the new technology .............................................. 140

3.9 Reduced line impedance .................................................................. 140
3.9.1 Technology description ................................................................. 140
3.9.2 Advantages of the new technology .............................................. 141

3.10 Trackside energy storage ............................................................... 141
3.10.1 Technology description ................................................................. 141
3.10.2 Advantages of the new technology .............................................. 141

3.11 Onboard energy storage .................................................................. 142
3.11.1 Technology description ................................................................. 142
3.11.2 Advantages of the new technology .............................................. 142

3.12 Waste heat usage by using absorption refrigeration ....................... 142
3.12.1 Technology description ................................................................. 142
3.12.2 Advantages of the new technology .............................................. 143

3.13 Superconducting traction transformer system ............................... 143
3.13.1 Technology description ................................................................. 143
3.13.2 Advantages of the new technology .............................................. 143

3.14 Medium frequency traction power supply ...................................... 143
3.14.1 Technology description ................................................................. 143
3.14.2 Advantages of the new technology .............................................. 143

3.15 Hybrid diesel electric propulsion with permanent magnet synchronous machines ................................................. 144
3.15.1 Technology description ................................................................. 144
3.15.2 Advantages of the new technology .............................................. 144

3.16 Reduction of vehicle coasting loss .................................................. 144
3.16.1 Technology description .......................................................................................... 144
3.16.2 Advantages of the new technology ........................................................................ 144

3.17 Active filtering technology to reduce input passive filter losses ....................... 144
3.17.1 Technology description .......................................................................................... 144
3.17.2 Advantages of the new technology ........................................................................ 145

3.18 Optimised management of medium voltage loads for energy saving - Optimisation of the auxiliary and cooling systems ......................................................... 145
3.18.1 Technology description .......................................................................................... 145
3.18.2 Advantages of the new technology ........................................................................ 145

3.19 Reuse of converter energy loss – Reuse of waste energy for the reduction of auxiliary consumption ................................................................. 145
3.19.1 Technology description .......................................................................................... 145
3.19.2 Advantages of the new technology ........................................................................ 145
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25kV 50Hz Traction Power Substation (TPS) or Feeder Station (typical single line diagram)</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>2x25kV 50Hz Traction Power Substation (TPS) or Feeder Station and main line connection (typical single line diagram)</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>2x25kV 50Hz Power Supply typical scheme for main line (half section)</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>25kV 50Hz typical Paralleling Station - single line diagram</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>25kV 50Hz typical Disconnecting/Sectioning Station - single line diagram</td>
<td>31</td>
</tr>
<tr>
<td>6</td>
<td>15kV 16.67Hz general diagram (Swedish railway system example)</td>
<td>32</td>
</tr>
<tr>
<td>7</td>
<td>General arrangement of a typical converter and transformer substation (15kV 16.67Hz system)</td>
<td>33</td>
</tr>
<tr>
<td>8</td>
<td>General arrangement of booster and autotransformer solutions (15kV 16.67Hz system)</td>
<td>35</td>
</tr>
<tr>
<td>9</td>
<td>Simplified diagram of 3kVdc traction system connection to the public grid (without HV power distribution loop)</td>
<td>36</td>
</tr>
<tr>
<td>10</td>
<td>Simplified diagram of 3kVdc traction system connection to the public grid (without HV power distribution loop)</td>
<td>36</td>
</tr>
<tr>
<td>11</td>
<td>Simplified diagram of 3kVdc traction system connection to the public grid (without HV power distribution loop)</td>
<td>37</td>
</tr>
<tr>
<td>12</td>
<td>Simplified sketch and cross-sectional view of the 3kV/1.5kVdc catenary system</td>
<td>39</td>
</tr>
<tr>
<td>13</td>
<td>Typical 3rd Rail 750Vdc Traction System Configuration</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>Hierarchy of HS signalling</td>
<td>44</td>
</tr>
<tr>
<td>15</td>
<td>Track circuits diagrams: (a) single rail, (b) double rail with insulating joints and impedance bonds, (c) double rail with tuned circuits</td>
<td>48</td>
</tr>
<tr>
<td>16</td>
<td>Contact Line system and TPS information flow to the OCC diagram</td>
<td>51</td>
</tr>
<tr>
<td>17</td>
<td>Typical HVAC chiller system (block diagram)</td>
<td>55</td>
</tr>
<tr>
<td>18</td>
<td>Typical HVAC direct expansion cooling system (block diagram)</td>
<td>56</td>
</tr>
<tr>
<td>19</td>
<td>Typical HVAC ventilation system (block diagram)</td>
<td>57</td>
</tr>
<tr>
<td>20</td>
<td>Typical Point Heaters System</td>
<td>59</td>
</tr>
<tr>
<td>21</td>
<td>Lighting and non-traction power supply subsystem general functional diagram</td>
<td>61</td>
</tr>
<tr>
<td>22</td>
<td>Supervision system for non-traction power supply subsystem diagram, (not part of the traction SCADA system)</td>
<td>63</td>
</tr>
<tr>
<td>23</td>
<td>Typical traction block diagram for V line = 1500 Vdc</td>
<td>66</td>
</tr>
<tr>
<td>24</td>
<td>Typical traction system electrical diagram for 1500 Vdc</td>
<td>69</td>
</tr>
<tr>
<td>25</td>
<td>Typical energy meter diagram</td>
<td>70</td>
</tr>
<tr>
<td>26</td>
<td>Typical traction system block diagram for 3000 Vdc</td>
<td>71</td>
</tr>
<tr>
<td>27</td>
<td>Typical electrical diagram for a traction system of V line = 3000 Vdc</td>
<td>74</td>
</tr>
<tr>
<td>28</td>
<td>Typical block diagram for 15 kV – 16 2/3 Hz traction system</td>
<td>75</td>
</tr>
<tr>
<td>29</td>
<td>Transformer for 15 kV – 16.67 Hz: electric circuit arrangement</td>
<td>77</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Table 1</td>
<td>List of acronyms.</td>
<td>17</td>
</tr>
<tr>
<td>Table 2</td>
<td>Typical measurements provided in 25kV 50Hz systems.</td>
<td>30</td>
</tr>
<tr>
<td>Table 3</td>
<td>Typical measurements provided in 15000 Vac 16.2/3 systems.</td>
<td>34</td>
</tr>
<tr>
<td>Table 4</td>
<td>Typical measurements provided in 1,5kV and 3kVdc systems.</td>
<td>38</td>
</tr>
<tr>
<td>Table 5</td>
<td>Typical measurements provided in 750Vdc systems.</td>
<td>41</td>
</tr>
<tr>
<td>Table 6</td>
<td>Electrical characteristic of an auxiliary converter for vehicles operating at 1500 Vdc</td>
<td>91</td>
</tr>
<tr>
<td>Table 7</td>
<td>Electrical characteristics of an auxiliary converter for vehicles operating at 3000 Vdc</td>
<td>91</td>
</tr>
<tr>
<td>Table 8</td>
<td>Electrical characteristics of an auxiliary converter for freight locomotives operating at 3000 Vdc</td>
<td>92</td>
</tr>
<tr>
<td>Table 9</td>
<td>Electrical characteristics of an auxiliary converter for high speed vehicles operating in multi-voltage traction subsystem (25 kV ac – 50 Hz, 3 kV dc, 1,5 KV dc)</td>
<td>92</td>
</tr>
<tr>
<td>Table 10</td>
<td>Electrical characteristics of an auxiliary converter for passengers coaches</td>
<td>93</td>
</tr>
<tr>
<td>Table 11</td>
<td>Main basic facts for frequency converters</td>
<td>103</td>
</tr>
<tr>
<td>Table 12</td>
<td>KPI 1</td>
<td>131</td>
</tr>
<tr>
<td>Table 13</td>
<td>KPI 2</td>
<td>132</td>
</tr>
<tr>
<td>Table 14</td>
<td>KPI 4</td>
<td>132</td>
</tr>
<tr>
<td>Table 15</td>
<td>KPI 5</td>
<td>133</td>
</tr>
<tr>
<td>Table 16</td>
<td>KPI 6</td>
<td>133</td>
</tr>
<tr>
<td>Table 17</td>
<td>KPI 7</td>
<td>134</td>
</tr>
</tbody>
</table>
**LIST OF ACRONYMS**

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Q converter</td>
<td>Four Quadrant Converter</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current: a continuous electric current that periodically reverses direction, usually sinusoidally</td>
</tr>
<tr>
<td>ACU</td>
<td>Auxiliary Converter Unit</td>
</tr>
<tr>
<td>ATO</td>
<td>Automatic Train Operation</td>
</tr>
<tr>
<td>ATP</td>
<td>Automatic Train Protection</td>
</tr>
<tr>
<td>BCU</td>
<td>Brake Control Unit</td>
</tr>
<tr>
<td>CAN-bus</td>
<td>Controller Area Network</td>
</tr>
<tr>
<td>CCU</td>
<td>Central Control Unit (Control of Vehicle)</td>
</tr>
<tr>
<td>Chopper</td>
<td>Component used to control the energy flow between the energy storage and the DC-Link</td>
</tr>
<tr>
<td>CMSS</td>
<td>Communication Management Subsystem</td>
</tr>
<tr>
<td>Coasting running</td>
<td>Vehicle driving mode through the effect of inertia, consisting to stop the traction effort when the speed limit is reached. The resumption of traction is carried out when the speed loss due to the coasting running reaches a certain value set by the driver</td>
</tr>
<tr>
<td>CPU</td>
<td>Control Processing Unit (also Central Processing Unit)</td>
</tr>
<tr>
<td>CR</td>
<td>Conventional Rail</td>
</tr>
<tr>
<td>CT</td>
<td>Current Transformer</td>
</tr>
<tr>
<td>D&amp;M</td>
<td>Diagnostic and Maintenance</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current: unidirectional flow of electric charge</td>
</tr>
<tr>
<td>DC/DC converter</td>
<td>Converter interfacing two Direct Current (DC) grids</td>
</tr>
<tr>
<td>DCS</td>
<td>Data Collection Service</td>
</tr>
<tr>
<td>DCU</td>
<td>Door Control Unit</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed Energy Resources</td>
</tr>
<tr>
<td>DG</td>
<td>Diesel Generator</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>DHS</td>
<td>Data Handling System</td>
</tr>
<tr>
<td>DIS</td>
<td>Driver Information System</td>
</tr>
<tr>
<td>DMI</td>
<td>Driver Machine Interface: MMI designed for railway application</td>
</tr>
<tr>
<td>DMU</td>
<td>Diesel Multiple Unit: train configuration with several connected cars, and propelled by diesel engines</td>
</tr>
<tr>
<td>DNO</td>
<td>Distribution Network Operator</td>
</tr>
<tr>
<td>DS</td>
<td>Demonstration Scenes</td>
</tr>
<tr>
<td>ECR</td>
<td>Electrical Control Room (see also OCC)</td>
</tr>
<tr>
<td>EETROP</td>
<td>Energy Efficient Train Operation</td>
</tr>
<tr>
<td>EIRENE</td>
<td>European Integrated Radio Enhanced Network</td>
</tr>
<tr>
<td>EMC</td>
<td>ElectroMagnetic Compatibility: it is the branch of electrical sciences which studies the unintentional generation, propagation and reception of electromagnetic energy with reference to the unwanted effects (Electromagnetic interference, or EMI) that such energy may induce</td>
</tr>
<tr>
<td>EMF</td>
<td>Energy Measuring Function</td>
</tr>
<tr>
<td>EMI</td>
<td>ElectroMagnetic Immunity</td>
</tr>
<tr>
<td>EMS</td>
<td>Energy Measuring System</td>
</tr>
<tr>
<td>EMT</td>
<td>Energy Meter</td>
</tr>
<tr>
<td>EMU</td>
<td>Electrical Multiple Unit: train configuration with several connected cars, and propelled by electric traction</td>
</tr>
<tr>
<td>ENA</td>
<td>Energy Network Association</td>
</tr>
<tr>
<td>ERA</td>
<td>European Railway Agency: ERA sets standards for European railways. Its mandate is the creation of a competitive European railway area, by increasing cross-border compatibility of national systems, and in parallel ensuring the required level of safety</td>
</tr>
<tr>
<td>ERTMS</td>
<td>European Railway Traffic Management System: it is made up of all the train borne, track side and line side equipment necessary for supervising and controlling, in real-time, the train operation according to the traffic conditions based on the appropriate Level of Application. (ERTMS/ETCS terminology)</td>
</tr>
<tr>
<td>ESS</td>
<td>Energy Storage System</td>
</tr>
<tr>
<td>ETCS</td>
<td>European Train Control System: a subset of ERTMS providing a level of protection against over-speed and overrun depending upon the capability of</td>
</tr>
</tbody>
</table>
the line side infrastructure (ERTMS/ETCS terminology)

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flywheel</td>
<td>Rotating mechanical energy storage system</td>
</tr>
<tr>
<td>FPP</td>
<td>Fixed Peripheral Post</td>
</tr>
<tr>
<td>GPRS</td>
<td>General Packet Radio Service</td>
</tr>
<tr>
<td>GS</td>
<td>Auxiliary converter’s control unit</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile communications: it is an open, digital cellular technology used for transmitting mobile voice and data services. GSM supports voice calls and data transfer speeds of up to 9.6 kbit/s, together with the transmission of SMS (Short Message Service). GSM operates in the 900MHz and 1.8GHz bands in Europe and the 1.9GHz and 850MHz bands in the US. The 850MHz band is also used for GSM and 3G in Australia, Canada and many South American countries. By having harmonized spectrum across most of the globe, GSM's international roaming capability allows users to access the same services when travelling abroad as at home. This gives consumers seamless and same number connectivity in more than 218 countries</td>
</tr>
<tr>
<td>GSM-R</td>
<td>Global System for Mobile communications – Railway</td>
</tr>
<tr>
<td>GSP</td>
<td>Grid Supply Points</td>
</tr>
<tr>
<td>GTW</td>
<td>Gateway</td>
</tr>
<tr>
<td>HHV</td>
<td>Very High Voltage (&gt; 230÷800kVac)</td>
</tr>
<tr>
<td>HS</td>
<td>High Speed</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage (&gt; 1÷230kVac)</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilating, and Air Conditioning: the technology of indoor or automotive environmental comfort. HVAC system design is a major sub-discipline of mechanical engineering, based on the principles of thermodynamics, fluid mechanics, and heat transfer</td>
</tr>
<tr>
<td>IDU</td>
<td>Integrated Diagnostic Unit</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated-Gate Bipolar Transistor</td>
</tr>
</tbody>
</table>
| IM | Infrastructure Manager: a company which is responsible for the railway infrastructure (tracks, lines, catenary system, substations depots, stations, bridges, tunnels etc.), their maintenance and building. Due to the ongoing liberalisation of the European railway markets national railway companies are being divided into IMs and railway operating companies (see RU). Other
stakeholders in the railway system and market are RUs, PTAs, SIs. Relevant industry association: www.uic.org

<table>
<thead>
<tr>
<th>KPI</th>
<th>Key Performance Indicators are used in the framework of the MERLIN project to determine and describe the energy performance of railway related technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LCC</td>
<td>Life Cycle Cost: total cost of ownership over the life of an asset</td>
</tr>
<tr>
<td>LIC</td>
<td>Lithium Ion Condenser</td>
</tr>
<tr>
<td>LITR</td>
<td>Local Interface Train Routing</td>
</tr>
<tr>
<td>LMSS</td>
<td>Line Management SubSystem</td>
</tr>
<tr>
<td>LPS</td>
<td>Lighting Power Station</td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage (50–1000 Vrms ac &amp; 120–1500 Vdc)</td>
</tr>
<tr>
<td>MCC</td>
<td>Multistation Control Centre</td>
</tr>
<tr>
<td>MLVS</td>
<td>Main Low Voltage Switchboard</td>
</tr>
<tr>
<td>MO</td>
<td>Ministry Order</td>
</tr>
<tr>
<td>MV</td>
<td>Medium voltage</td>
</tr>
<tr>
<td>MVB</td>
<td>Multifunction Vehicle Bus: it is a field bus, consisting of a single or dual data line used in train control systems, and described in IEC 61375</td>
</tr>
<tr>
<td>OCC</td>
<td>Operation Control Centre (also indicated as ECR)</td>
</tr>
<tr>
<td>OHCS</td>
<td>OverHead Catenary System</td>
</tr>
<tr>
<td>PEC</td>
<td>Power Electronic Control</td>
</tr>
<tr>
<td>PFS</td>
<td>Peripheral Fixed Site</td>
</tr>
<tr>
<td>PIS</td>
<td>Passenger Information System: electronic system which provides real-time information to passengers</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller: digital computer used for automation of electromechanical processes</td>
</tr>
<tr>
<td>PMSM</td>
<td>Permanent Magnet Synchronous Motors</td>
</tr>
<tr>
<td>PS</td>
<td>Power Supply</td>
</tr>
<tr>
<td>PT</td>
<td>Peripheral terminal</td>
</tr>
<tr>
<td>-----</td>
<td>---------------------</td>
</tr>
<tr>
<td>PV</td>
<td>Photo Voltaic</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse With Modulation</td>
</tr>
<tr>
<td>RBC</td>
<td>Radio Block Centre</td>
</tr>
<tr>
<td>RD</td>
<td>Royal Decree</td>
</tr>
<tr>
<td>REB</td>
<td>Relocatable Equipment Building</td>
</tr>
<tr>
<td>RiM</td>
<td>Magnesium alloyed copper conductors</td>
</tr>
<tr>
<td>RIO</td>
<td>Remote Interface Unit</td>
</tr>
<tr>
<td>RS</td>
<td>Rail System</td>
</tr>
<tr>
<td>RTU</td>
<td>Remote Terminal Unit</td>
</tr>
<tr>
<td>RU</td>
<td>Railway Undertaker (also Railway Undertaking Company): a company which operates railway vehicles and offer railway transport services (freight and/or passenger). Due to the ongoing liberalisation of the European railway markets national railway companies are being divided into RUs and Infrastructure Managers (see IM). Other stakeholders in the railway system and market are IMs, PTAs, SIs. Relevant industry association: <a href="http://www.uic.org">www.uic.org</a></td>
</tr>
<tr>
<td>RX</td>
<td>Track circuit receiver</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervision Control &amp; Data Acquisition system</td>
</tr>
<tr>
<td>Scenario</td>
<td>Set of use cases grouped under certain boundaries, conditions and a common framework. In MERLIN five scenarios are defined. Each of them runs several uses cases on the same environment (e.g. same topography, same electrification)</td>
</tr>
<tr>
<td>Smart grid</td>
<td>Electric Network using digital technology to monitor energy supply and consumption characteristics with the aim of reducing costs and increasing reliability</td>
</tr>
<tr>
<td>STTS</td>
<td>Superconducting Traction Transformer System</td>
</tr>
<tr>
<td>Supercapacitor</td>
<td>Electric Double Layer Capacitor: electrochemical capacitors having higher performances than common electrolytic capacitors, especially as far as energy density is concerned</td>
</tr>
<tr>
<td>TCN</td>
<td>Train Communication Network: it is a hierarchical system of field busses for railway application. It is used to exchange process data and message data. TCN is being described with IEC 61375</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>TCP/IP</td>
<td>Transmission Control Protocol and Internet Protocol</td>
</tr>
<tr>
<td>TCS</td>
<td>Train Control System</td>
</tr>
<tr>
<td>TCU</td>
<td>Traction Control Unit</td>
</tr>
<tr>
<td>TecRec</td>
<td>Technical Recommendation: voluntary standard between industry and RU</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
</tr>
<tr>
<td>Timetable</td>
<td>A timetable is the description of all train movements (journeys) and all temporary restrictions which are planned for a given operational day. It contains all description of train journeys following imposed routes, under the form of a planned arrival time to and a departure time from each station</td>
</tr>
<tr>
<td>TPA</td>
<td>Third Party Access</td>
</tr>
<tr>
<td>TPH</td>
<td>Track Paralleling Huts</td>
</tr>
<tr>
<td>TPS</td>
<td>Traction Power (supply) Substations</td>
</tr>
<tr>
<td>TRU</td>
<td>Transformer Rectifier Unit</td>
</tr>
<tr>
<td>TSI</td>
<td>Technical Specification for Interoperability: specifications drafted by the European Railway Agency and adopted in a Decision by the European Commission, to ensure the interoperability of the trans-European rail system</td>
</tr>
<tr>
<td>TSSS</td>
<td>Train Spacing SubSystem</td>
</tr>
<tr>
<td>TX</td>
<td>Track circuit transmitter</td>
</tr>
<tr>
<td>UIC</td>
<td>International Union of Railways, Union Internationale des Chemins de fer</td>
</tr>
<tr>
<td>UNIFE</td>
<td>Professional association for the railway supply industry, directly and through national associations representing over 900 European companies</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptible Power Supply</td>
</tr>
<tr>
<td>Use case</td>
<td>A story line, that starts from preconditions to reach a final state or goal through a number of steps, where interactions between the components of a system are also defined. In MERLIN each use case runs within a framework (i.e. scenario)</td>
</tr>
<tr>
<td>Validation</td>
<td>The process of determining the degree to which a model or simulation is an accurate representation of the real world from the perspective of the intended uses of the model or simulation</td>
</tr>
<tr>
<td>VCU</td>
<td>Vital Control Unit</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>WTB</td>
<td>Wire Train Bus</td>
</tr>
</tbody>
</table>

Table 1: List of acronyms.
1. INTRODUCTION

As reported in the MERLIN project Description of Work (DoW), the main scope of the first work package (WP1) is to identify, describe and characterize the key elements of the different sub-systems of a mainline railway system leading to the development of a global electricity consumption map defining levels of energy consumption. In particular, the description of railway network sub-systems is developed within the first task of WP1, while the second task is committed to the elaboration of the global consumption map.

This document represents the main deliverable (D1.1) of the WP1 first task and reports the description and characterization of a generic mainline railway system. The railway system can be considered as a closely-knitted integration of a number of sub-systems which interact continuously with each other influencing the global energy consumption. Thus, in this document, the structure of a generic railway networks is described through the definition and characterization of its sub-systems and main components. The definition of the proper set of category for the system description and the identification of different railway’s sub-systems is reported in Section 2. Furthermore the document reports, in Section 4, an overview on the state of the art of the main technological solutions (such as reversible sub-stations or energy storage systems) that are now increasingly used to reduce the global system’s energy consumption in modern railway networks. Finally, in Section 5, the document covers the description of main railway system’s non-electrical constraints, related to legislation, energy supply and consumption contractual commitments, and possible control procedures.

The deliverable is built referring to existing data and information available from the WP1 members (e.g. infrastructure managers and operators) and collected during the Task 1.1 execution. Moreover, previous European research initiatives are taken into account for the development of this deliverable. In particular the data and information coming from RailEnergy project are considered for the identification and classification of railway network sub-systems.

In order to clarify further the main objectives of the project, the scope of this deliverable and its relations with RailEnergy project, an abstract on main MERLIN project’s aim and a brief summary on RailEnergy research project are reported below.

1.1 THE MERLIN PROJECT

MERLIN’s main aim and purpose is to investigate and demonstrate the viability of an integrated management system to achieve a more sustainable and optimised energy usage in European electric mainline railway systems.

MERLIN will provide an integrated optimisation approach that includes multiple elements, dynamic forecasting supply-demand scenarios and cost considerations to support operational decisions leading to a cost-effective intelligent management of energy and resources through:

- Improved design of existing and new railway distribution networks and electrical systems as well as their interfaces with the external power network and considering network interconnections.
- Better understanding of the influence on energy demand of operations and operational procedures of the different elements of the railway system.
• Identification of technologies and solutions able to further contribute to the optimisation of energy usage.
• More efficient traction energy supply based on optimised use of resources.
• Understanding of the cross-dependency between these different technological solutions to define optimum combinations for optimised energy usage.
• Improving cost effectiveness of the overall railway system.
• Contribution to European standardisation (TecRec).

MERLIN will also deliver the interface protocol and the architecture for energy management systems in the railway domain, combining the technical development with new business model that would enable and foster their application.

Considering the project's context, an overall description of the electric mainline railway systems has to be developed, in order to provide a common representation of the railway network.

In particular, this deliverable represents the backbone for the railway system description, identifying the boundary of the framework for the definition of the reference architecture of the Railway Energy Management (REM) system, developed within WP2.

### 1.2 THE RAILENERGY PROJECT EXPERIENCE

#### 1.2.1 The interface of RailEnergy and MERLIN

Energy management is already a key issue for railway systems and it will continue to be for the foreseeable future. The variety of operational scenarios within the system adds complexity to the development of solutions suitable for all. The assessment tools developed by RailEnergy lack an integrated approach, focusing instead on certain elements of the system in isolation such as trains. Network models tend to also be assessed in isolation without considering their links to other networks or any potential alternative scenarios.

Critically, these models tend to omit the impact of the timetable on the variation in emission levels, energy usage and associated costs over different periods of time.

International collaborative initiatives such as RailEnergy have already successfully identified technologies able to contribute to the optimization of energy usage as well as developed tools that support the assessment of such contribution. SmartEnergy will go beyond these to provide an integrated optimization approach that includes multiple elements, dynamic forecasting supply-demand scenarios and cost considerations to support operational decisions leading to a cost-effective intelligent management of energy and resources.

The aim of this document is to deliver the basic information about technologies and methodology developed in the RailEnergy project in order to build a solid groundwork for the MERLIN project. Already developed technologies, strategies and experiences shall be used in order to act cost effective as well as to achieve as much benefit as possible out of the MERLIN project.
1.2.2 RailEnergy outcome

General remark
The public marketing of RailEnergy’s results was one of the main points of the Commission as well as of UNIFE and UIC. A public website is alive where several tools are offered to operators and others. The development work was mainly coordinated by UNIFE, UIC, Macroplan and D’Appolonia with support of RailEnergy’s TMT and MERLIN’s WP07 and WP08 should benefit from this experience. Please check: http://www.railenergy.eu/.

Relevant baseline figures and scenarios for selected reference systems
In order to evaluate any energy efficiency potential in the rail sector studies were led both in terms of statistics and for “single vehicle” based performance. The purpose of this first objective was to get the metrics in place so the whole sector was in fact discussing from the same baseline and with the same measuring units.

All information concerning relevant baseline figures and the scenarios descriptions were investigated and were presented in particular:

- Energy data and 2020 scenarios for the European railways
- Country profiles with information on national energy context
- Set of agreed Key Performance Indicators (KPIs), their definitions and implications for the project success criteria
- Demo scene reports and Performance baseline

RailEnergy’s approach to commonly define and confirm baselines and measuring units within the consortium shall be important for MERLIN’s subproject WP01 and WP02. The usage of confirmed KPI’s is essential for the simulation, evaluation and validation process within the MERLIN project. Therefore MERLIN’s WP03, WP04, WP05 and WP06 should participate from the experiences made in the RailEnergy project. The KPI’s are described in the Appendix. The country profiles with the information on the national energy context can be useful for WP1, T1.2.

System based concept for modelling energy consumption
A system-based concept for modelling energy consumption was developed in “RailEnergy Global Model” in which the Energy Balance of the Whole System was supported by models with commercial simulation tools and measuring energy consumption. The methodology to model the railway system for simulation was developed and describes the system boundaries, interfaces, structure and input/output parameters. The work was the structural base for performing the system simulations to design specifications. The implementation of a common data base that can be used to implement the Global model approach was developed.

MERLIN’s WP03, WP04, WP05 and WP06 should benefit from the experiences of simulation, evaluation and validation made in RailEnergy. This process is described in detail in the Appendix. The main players were: Macroplan, Alstom, Ansaldo Breda, Bombardier, Enotrac and Siemens. The development of the strategy of the process was done by D’Appolonia, Macroplan and Siemens.
Common and standardized methodology to determine energy consumption by rail sub-systems and components

The purpose of this objective was to produce an industry wide standard for prediction and verification of single vehicle performances. Energy efficient vehicle solutions for the operators in a common language of performance were delivered. Technical Recommendations (TecRec) were propose to UIC/UNIFE group and today are still in study. The aim is to publish them as a European Norm. The standards are actually focused on the communication between manufacturers and operators – typically in procurement projects where the operator would like to achieve low life cycle costs and a high energy performance.

Technical recommendations were developed for two work packages of RailEnergy. One TecRec is focused on operational issues e.g. load cycles of trains. The other one is related to the specification of a technical function e.g. description of functions of a reversible DC substation. However TecRecs were developed within RailEnergy for operational as well as functional recommendations. The experiences were made by different operators like SBB and ÖBB as well as Alstom and RFI. The support was achieved by D’Appolonia, UNIFE and UIC. MERLIN’s work packages, especially WP07 and WP08 should benefit from the experiences of the mentioned companies and organisations.

An integrated simulation tool for energy consumption and life cycle cost

This objective was relative to two different issues. The comparable simulations of the of energy consumption were done by the Global Model members. The calculation of Life Cycle Costs for these scenarios was done by another work package which was directly connected to the Global Model.

The methodology of RailEnergy is described in detail in the Appendix. MERLIN’s WP03, WP04, WP05 and WP06 should benefit from the experiences. In order to avoid the battology of misjudgement of time, costs and resources needed for evaluation of energy demand and Life Cycle Costs it is strongly recommended to contact the companies which were involved in RailEnergy’s WP1 and WP2. They main players were: IZT, Macroplan, D’Appolonia, UNIFE and UIC, Alstom, Ansaldo Breda, Enotrac and Siemens.

An integrated railway energy efficiency management approach & decision support tool

This objective was to define a web-based database and calculator for the assessment of various energy efficiency strategies for operators and infrastructure managers both on an operational and technical as well as on a strategic level. The strategic evaluation was based on a cost benefit/cost effectiveness methodology including the LCC perspective based on two core elements: The decision support tool and the knowledge base. The output of this work package was a database capable of carrying out the assessments based on the 3 demonstration scenarios already defined and supported by a database of European rail traffic and their energy efficiency characteristics.

The development of the strategic assessment process was done by D’Appolonia and Macroplan with support of Siemens. MERLIN’s WP06 should benefit from the experiences of strategic assessment in RailEnergy.
New energy efficiency technologies and validated concepts and solutions for the whole railway system

This objective refers to the technologies that were developed in the technical subprojects which are related to “hardware”.

The scope of the first subproject was to improve the specific efficiency of an area of the track feeding as well as the complete design and architectures of the whole feeding systems, in order to have a completely new approach to energy savings.

Another subprojects was focused on the vehicles, in particular assessing the benefits of electrical brake energy recovery and new battery-fed sustainable system, establishing targets and check energy storage related safety issues, formulating and optimize a concept for waste-heat reuse in passenger carrying Multiple Units and developing a user friendly interaction with the driver (DMI) for an existing Drive Style Manager for both multiple, units and locomotives.

The objectives of the third subproject was focused on the vehicles as well but covered in contradiction the subproject above the analysis and modelling of energy flow inside the energy generation and distribution system, the distribution of medium-frequency energy, innovative energy efficient and mass reduced diesel electric propulsion systems, and superconducting transformers and inductances for the railway traction application.

The last subproject also covered the analysis and modelling of energy flow inside the energy generation and distribution system, but focuses on control algorithms for traction systems, auxiliary power system topologies, and innovative converter cooling systems.

The outcomes of these subprojects are mainly relevant for MERLIN’s WP04. An overview and descriptions of the technologies developed are given in the Appendix.

Strategies for incentives, pricing, and policies to enhance exploitation of RailEnergy solutions in the sector

It identified and provided an assessment and classification of alternative incentives for the exploitation of energy efficiency solutions in the railway sector including policy and regulative measures, economic and standardization incentives.

The experiences of this RailEnergy subproject should be relevant for MERLIN’s WP06 and WP07. Additionally they are relevant for definition of MERLIN’s prospective business cases. The work was mainly done by the organizations UIC and UNIFE and the companies D’Appolonia and IZT.

1.2.3 RailEnergy references


2. THE RAILWAY SYSTEM

Purpose of this section is, within the overall description of main line railway network structures and characterization of their key subsystems, to identify and describe those railway subsystems and components influencing the overall energy consumption.

The railway system has a complex configuration scheme covering a wide range of subsystems with different functions and interfaces.

The approach, which has been used in order to achieve the aim of this section, has led to classify the subsystems in the main categories of:

- traction power related and power supply subsystems
- operational related subsystems
- auxiliary subsystems

both for fixed infrastructures and rolling stock subsystems.

First category of traction power related subsystems is clearly referred to those parts of the railway which are to be associated with traction needs and therefore are mostly influencing energy consumption.

The second category of operational related subsystems mainly refers to communication and data transmission, control and diagnostic architecture, signalling subsystems.

It should be noted that within the railway structure such subsystems are usually critical for safety and operation; therefore in most cases the relevant electrical loads are to be dealt as passive loads, not to be included within the context of energy and power rationalization.

However a short description is included, in order to highlight their impact on the overall railway structure, and the control/communication issues and interfaces with the other categories.

The last category of auxiliary subsystems is mainly related with non traction loads and components and, depending on situations and characteristics, can have an impact on energy consumption.

However, it should be noted that also in this category some subsystems may be critical in specific situations (e.g. Point Heating Devices or critical ventilation systems), being in this circumstance not subject to energy optimization issues.

As highlighted above, the three different categories are to be applied either to fixed facilities/infrastructures or to rolling stock.
2.1 Fixed Facilities, Infrastructures and Wayside Related Subsystems

Fixed facilities, Infrastructures and Wayside related systems can be classified as follows:

1. Traction power related and power supply systems.
2. Operational related systems.
3. Auxiliary systems

2.1.1 Traction power related and power supply systems

In the following a description of traction power related and power supply systems, to be associated to railway fixed facilities and infrastructures, is included.

The variety of subsystems which can be found within the different European railway network is very wide, however the description below is covering the main traction subsystem typologies, which are listed on the basis of different nominal voltage/frequency levels, as can be found below:

- 25kV 50Hz high speed railway system
- 15kV 16.67Hz railway system
- 3kV and 1.5kVdc railway system
- 750Vdc railway system

For each typology, characterization is also divided in the further subparagraphs also listed below:

- Interface with external power network
- Traction power and power supply subsystem
- Traction line (overhead catenary) subsystem

Moreover, for each traction typology and for each voltage level found within the relevant distribution system, information about typical measurements availability (local and/or remote) is provided.

However, it should be noted that quantity and typology of the measurements can significantly vary depending on the characteristics of the different systems. Particularly, in the tables shown in the following paragraphs, measurements which could not be present in some systems are highlighted.

25kV 50Hz high speed railway system

It should be noted firstly that 25kV systems have mainly been related with the need of reducing journey times and therefore with high speed requirements. Since the 1970’s there have been developments within the various railway systems worldwide (in 1964, Japan built the first rail service capable of 220 km/h on the Tokyo-Osaka line), and in 1975, in Europe, the first high-speed line that connected Paris and Lyon in less than two hours was built. This was considered a success, and subsequent high-speed railway lines have been built across Europe.

Over the years, the majority of high speed railway systems in Europe have been developed considering a single phase 25kV – 50Hz (or 60Hz, depending on the Country main power distribution network) electrical system rather than a DC power system (i.e. 3 kVdc). Usually, this is
called “1x25kV” power system. Compared with DC and lower-voltage AC systems, this presents an overall economic advantage; in particular, the number of traction power substation can be heavily reduced.

Later on, in order to further improve the efficiency of the High Speed Railway electrical system, the typical “1x25kV” power systems have steadily been upgraded to the “2x25kV” (±25kV) power system. The aim of this is to increase the distance between adjacent traction power substations to almost double, and to reduce EMC/EMI issues. Thanks to the particular electrical configuration of the 2x25kV power system, it is possible to increase the relevant voltage step (thus optimizing the power transfer) without increasing the equipment insulation class.

Below are some typical diagrams for “1x25kV” and “2x25kV” for Railway Power Systems:

Figure 1: 25kv 50Hz Traction Power Substation (TPS) or Feeder Station (typical single line diagram).
Figure 2: 2x25kv 50Hz Traction Power Substation (TPS) or Feeder Station and main line connection (typical single line diagram).
Figure 3: 2x25kV 50Hz Power Supply typical scheme for main line (half section).
Interface with External Power Network
As far as 1x25kV” or “2x25kV” Railway Systems are concerned, traction power substations are normally directly connected to the main power distribution network; usually there is no power distribution loop to interconnect adjacent TPS. This is called “antenna” power connection.

It should be noted that a power distribution loop may be provided by the External Power Supply Distribution Network Authority.

Traction power and power supply subsystem
The purposes of the traction power substation are:

- to lower the voltage level of the incoming line (from the Power Supply Distribution Authority) to the proper Overhead Catenary System Level, through the main transformers;
- to protect the TPS equipment (in particular, the main transformer) and the OHCS, through the use of circuit breakers.

Switch Disconnectors or isolators could also be provided to allow the traction power system reconfiguration depending on the railway system operator requirements.

Along the line, Paralleling Stations are provided to enable a robust voltage level at the OHCS in lieu of additional TPS locations. These may be incorporated into a Disconnection/Sectioning Station. Below a typical PS single line diagram is given:

![Single line diagram of a 25kV Paralleling Station](image)

**Figure 4: 25kV 50Hz typical Paralleling Station - single line diagram.**

For each of the voltage levels found within the distribution system, the following measurements can be typically provided, locally (L=remote) and/or remotely (R=remote) via SCADA system:
**Table 2: Typical measurements provided in 25kV 50Hz systems.**

Note: in the table shown above, measurements indicated with “∗” could not be present in some Systems.

**Traction line subsystem**

Generally speaking, the OHCS is the interface point between the TPS and vehicles and it has to guarantee robust transfer of electrical traction power.

A typical “2x25kV” system consists of:

- Overhead catenary system (+ 25 kV), including:
  - Contact wire (Cu/100 to 150 mm² typically).
  - Messenger/Catenary wire (Cu/70 to 170 mm² typically).
- Overhead feeder wire (-25 kV - Al/300 to 400 mm² typically).
- Earthing and current return circuit including:
  - Longitudinal earthing buried electrodes (Cu/95mm² typically).
  - Earthing wires (Al/150mm² typically).
  - The tracks.
For a typical “1x25kV” system, the overhead feeder wire is replaced with a Return Conductor and booster transformer system, the conductor size for which can generally vary from about 150mm$^2$ or 270 mm$^2$ depending on application.

Disconnecting Stations are equipped with Switch Disconnectors to allow the traction power system reconfiguration depending on the railway system operator requirements.

Below a typical sketch for a Disconnecting Station is given:

![Figure 5: 25kV 50Hz typical Disconnecting/Sectioning Station - single line diagram.](image)

**15kV 16.67Hz railway system**

The railways in Germany, Austria, Switzerland, Sweden and Norway are electrified with 15 kV 16.7 Hz. The performance of the system is similar to 25 kV 50 Hz and both are suited for high speed rail service according to TSD. The typical type of this kind of electrification is the Swedish railway system.

*Interface with External Power Network*

Typically main line trains are fed by a nominal 15 kV, which actually is 16.5 kV 16⅔ Hz, 1 phase AC overhead contact line system, or simply called catenary. All power is taken from the 50 Hz public grid. Furthermore, a high voltage feeder line (usually 132kV = 2x66 kV, 16¾ Hz, 2 phases) is installed in addition to reduce power flows on the catenary and to reduce the number of supply stations.
Figure 6: 15kV 16.67Hz general diagram (Swedish railway system example).

**Traction power and power supply subsystem**

The public grid is generally connected to the railway power supply grid via power supply stations or converter substations. The converter substations consist mainly of:

- Converter supply section changing voltage level, frequency and number of phases between the national public grid and the catenaries. That is between different voltage levels (on the primary side usually: 220, 130 70, 50 kV), 50 Hz, 3 phases to 15 kV, 16⅔ Hz, 1 phase on the catenary. The voltage levels on the primary side are transformed down to appropriate level before the converters. This level depends on the converter type. Rotary converters receive 6.3 kV. Other usual level is 22 kV.

- Transformer supply section changing voltage levels between the catenaries and the HV feeder lines. That is from 15 kV, 16⅔ Hz, 1 phase to 132 kV, 16⅔ Hz, 1 phase (feeder).

- Auxiliary transformers. Auxiliary equipment is operated at 50 Hz.

The railway supply network contains also:

- Transformer substations changing voltage levels between the HV feeder lines and the catenaries. That is typically from 132 kV, 16⅔ Hz, 1 phase (feeder) to 15 kV, 16⅔ Hz, 1 phase.

- Booster or auto transformers managing return currents;
• Shunt harmonic impedances to mitigate harmonic propagation. Mostly as active filters on locomotives.

The following diagram shows the general arrangement of a typical converter substation. There is a group of frequency converter units feeding the contact lines as well as arrangements to feed the transmission line. Furthermore in the figure transform substations and booster transformers are highlighted.

![Diagram](image)

**Figure 7: General arrangement of a typical converter and transformer substation (15kV 16.67Hz system).**

Typical distance between transformers stations is 40-50 km. Typical distance between converter stations is 60-90 km.

For each of the voltage levels found within the distribution system, the following measurements can be typically provided, locally (L=remote) and/or remotely (R=remote) via SCADA system:
Table 3: Typical measurements provided in 15000 Vac 16.2/3 systems.

Note: in the table shown above, measurements indicated with "*" could not be present in some Systems.

Moreover, total energy is sent in to a remote system and it is not available locally except the total value which can be read manually at a converter station. By having this measurement the total losses of a converter station can be measured.

**Traction line subsystem**

At the beginning of electrification, return current was sent trough the ground, so called direct feed system. That produced big electromagnetic interference problems. The booster transformer technology was early introduced in order to mitigates such problems by minimize the current leakage trough the ground. It consists of a transformer connecting the catenary and a return line and having the same number of windings on both sides. In this way currents trough catenary and the return line are forced to be equals.

A drawback is that the booster transformer feed has higher impedance that the direct feed.

Later auto-transformer, AT, feeding is also used. The use of auto-transformers gives, compared to a system with booster-transformers, a lower voltage drop, higher power capability and the possibility to place converter stations at greater distances from each other. The system uses a second feeder with a 180° phase difference from the contact wire, which doubles the voltage level of the system.
As the transformers used is not ideal, the AT-system do not fully forces the current to flow back in the negative feeder and some of the current flows through other parts of the rail and can cause problems with nearby cables.

![Diagram of booster and autotransformer solutions](image)

**Figure 8: General arrangement of booster and autotransformer solutions (15kV 16.67Hz system).**

### 3kV and 1.5kV DC railway system

This supply system is always used for heavy traction railways in its 3kV version, while it can be used also for light railways at the lower voltage level of 1.5kV. The 1500V system was introduced in the southern and southwestern part of France; the power limitation at about 4-5MW for this type of system lead to the introduction of 3kV system in the late '20s.

Several Countries in Europe have conventional railways supplied at these two voltage levels: Italy, Spain, Poland, Belgium, Russia, part of Czech Rep. (at 3kV), Netherlands and France (at 1.5kV) to cite some. Light railways at 1500V, limited to a small region or around a populated area, may be found in UK, Denmark and Istanbul.

The main advantage of a DC supply is that the longitudinal voltage drop along the catenary is only due to the longitudinal resistance and inductive reactance is always zero. Furthermore, the main power for traction loads is supplied by the public grid (HV, 50-60Hz) through the traction power substations, without unbalancing the load sharing among phases. Due to the DC power supply mode, traction substations can be parallel connected along the line, thus reducing the voltage drops.

On the other side, DC power distribution for traction purposes introduces the stray current corrosion issue (which is almost negligible for AC system).

**Interface with External Power Network**

The main power for traction loads is supplied by the public grid (HV, 50-60Hz) through the traction power substations; depending on the overall power system architecture and requirements traction power substations can be either directly connected to the main power distribution net or fed by an HV power distribution loop.
Figure 9: Simplified diagram of 3kVdc traction system connection to the public grid (without HV power distribution loop).

Figure 10: Simplified diagram of 3kVdc traction system connection to the public grid (without HV power distribution loop).

Traction power and power supply subsystem
The purposes of the traction power substation are

- to lower and rectify the voltage level of the incoming line (AC power, 50-60HZ) to the proper Overhead Catenary System Level (1500-3000Vdc), through the main transformers and the relevant rectifiers.
- to protect the TPS equipment (in particular, the main transformer and the rectifier) and the OHCS, through the circuit breakers.

Switch Disconnectors are also provided to allow the traction power system reconfiguration depending on the railway system operator requirements.

Below a typical TPS single line diagram is given:
Figure 11: Simplified diagram of 3kVdc traction system connection to the public grid (without HV power distribution loop).

Where:

- SAT<sub>P</sub> is the 3-phase (incoming line) disconnector switch;
- I<sub>P</sub> is the 3-phase (incoming line) circuit breaker;
- SAT<sub>S</sub> is the 3-phase (bus bar) disconnector switch;
- SAT<sub>g</sub> is the 3-phase (incoming rectifier group) disconnector switch;
- I<sub>g</sub> is the 3-phase (incoming rectifier group) circuit breaker;
- T<sub>g</sub> is the transformer of the rectifier transformer unit;
- S<sub>m</sub> is the 3-phase (incoming rectifier) disconnector switch;
- S<sub>S</sub> is rectifier double pole (positive and negative) disconnector switch;
- S<sub>a</sub> is the positive traction line disconnector switch;
- J<sub>L</sub> is the positive traction line high speed circuit breaker.

The typical traction power substation is equipped with n. 2 rectifier group (parallel connected) and the overall power availability is lower than 12MW. Generally speaking, the average distance between two adjacent traction power substations is 20km.

For each of the voltage levels found within the distribution system, the following measurements can be typically provided, locally (L=remote) and/or remotely (R=remote) via SCADA system:
Table 4: Typical measurements provided in 1.5kV and 3kVdc systems.

Note: in the table shown above, measurements indicated with "*" could not be present in some Systems.

**Traction line subsystem**

Generally speaking, the overhead catenary system is the interface point between the traction power substation and vehicles and it has to guarantee the relevant traction power transferring.

Depending on the installed power along the traction system, the catenary system can have different cross sections; typically a 540mm² cross section is provided as follow:

- Contact wire (Cu/2x150mm²)
- Messenger wire (Cu/2x120mm²)

Traction return current flows back to substations through the running rails path.

Below a simplified sketch of the catenary system is given:
Switch Disconnectors are also provided to allow the traction power system reconfiguration depending on the railway system operator requirements.

### 750V DC railway system

Although 750 Vdc is normally considered to be a low voltage level to be used for railways, some railway lines are electrified by using this value, with particular reference to some systems which are present in the U-K.

**Interface with External Power Network**

The AC three-phase utility supply from DNO provides the feed for the DC traction power substation. The electrical supply is fed to the railway at typically 132kV, 66kV or 33kV and the electrical power is then distributed through a separate AC network at a medium voltage of typically 33kV (although other voltage values can be envisaged). This supply is used to provide a 750Vdc supply to the traction power network through Substations (SS) located at varying intervals around the railway network.

It is worth noting that the Grid Supply Points (GSP), shown in the following figures, utilized for providing power to the DC network are generally not sole use sites, unlike those which provide power to the AC network.

Sole use refers to the GSP providing power to the railway network alone, with no other customers fed off the same circuit.

As such, there are a number of additional feeders that the GSP transformer is connected to. This limits the amount of control the railway infrastructure manager has regarding increasing loading on the equipment (this fact comes into consideration when assessing timetable changes and associated enhancement options).
Traction power and power supply subsystem

At the Substations, the incoming supply is transformed and rectified using 6 or 12 pulse rectifiers, to provide the DC traction supply through the use of a Transformer Rectifier Unit (TRU). There are a range of TRUs, specified by both their rating (i.e. 1MW, 2MW, 2.5MW or 3MW) and overload capability (i.e. Class F, Class G). The positive pole is connected to the conductor rails through the high speed DC circuit breakers; the negative return is via the running rails.

In addition to Substations, Track Paralleling Huts (TPH) are also located throughout the traction power network. Though they do not offer any power conversion capabilities, they do improve the voltage profile through paralleling of the individual electrical sections and enable further sectioning capabilities.

The spacing of SSs and TPHs is based on the power demand of the connected local network. Generally, there is 2-3km spacing between sites but factors such as the availability of land, the position of junctions and crossovers and the provision of road access to a particular site sometimes make it impossible to position a substation in precisely the calculated position.

A very important consideration in the spacing of substations is that the track feeder circuit breakers must be able to discriminate between the maximum load current and the fault current.

In areas of light load, the network will generally comprise of a SS followed by a TPH and then again by a SS, however this would be confirmed via modelling.

In areas of medium to high load, the network will generally comprise of continual TPS with the rating and number of the installed TRUs dependent on the anticipated loading, confirmed via modelling.

![Figure 13: Typical 3rd Rail 750Vdc Traction System Configuration.](image)
A Substation consists of, but is not limited to, the following main components:

- Three winding transformers to provide the correct input voltage for the rectifiers from the incoming 3-phase AC, typically at 33 kV
- AC circuit breakers for fault protection
- AC switches and isolators for the selection of the incoming feeder, transformer and to permit emergency feeding conditions and maintenance access
- Silicon diode rectifiers. Usually, each rectifier consists of two 6-pulse bridges, connected in parallel or in series thus producing overall 12-pulse output ripple
- DC switches and isolators to select which rectifier is to be operational, for isolating track sections
- High-speed DC circuit breakers for protecting the traction power network along with the trains. These are highly specialized and costly components but necessary because of the physical difficulty of breaking a large DC current in an inductive circuit.

The Track Paralleling Hut contains the same equipment associated with the 750V DC network but no High voltage ac stage or power conversion related equipment.

For each of the voltage levels found within the distribution system, the following measurements can be typically provided, locally (L=remote) and/or remotely (R=remote) via SCADA system:

<table>
<thead>
<tr>
<th></th>
<th>HV incoming</th>
<th>MV incoming/outgoing</th>
<th>Traction MV</th>
<th>Line feeder</th>
<th>Aux. serv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>voltage</td>
<td>L/R *</td>
<td>L/R</td>
<td>L/R</td>
<td>L/R *</td>
<td>L *</td>
</tr>
<tr>
<td>current</td>
<td>L/R *</td>
<td>L/R</td>
<td>L/R</td>
<td>L/R *</td>
<td>L *</td>
</tr>
<tr>
<td>active energy</td>
<td>L *</td>
<td>L *</td>
<td></td>
<td></td>
<td>L *</td>
</tr>
<tr>
<td>reactive energy</td>
<td>L *</td>
<td>L *</td>
<td></td>
<td></td>
<td>L *</td>
</tr>
<tr>
<td>total energy</td>
<td></td>
<td></td>
<td>L</td>
<td></td>
<td>L</td>
</tr>
<tr>
<td>active power</td>
<td>L *</td>
<td>L</td>
<td></td>
<td></td>
<td>L</td>
</tr>
<tr>
<td>reactive power</td>
<td>L *</td>
<td>L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>frequency</td>
<td>L *</td>
<td>L *</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TR oil temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L</td>
</tr>
<tr>
<td>TR windings temp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L</td>
</tr>
<tr>
<td>TR core temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L</td>
</tr>
<tr>
<td>under load tape changer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L *</td>
</tr>
</tbody>
</table>

Table 5: Typical measurements provided in 750Vdc systems.
Note: in the table shown above, measurements indicated with ‘*’ could not be present in some Systems.

Traction line subsystem
Conductor rails are the means by which electric units or locomotives can obtain 750Vdc power. Collector shoes mounted on the train make a sliding contact with the top of the conductor rail and, in conjunction with the contact between the wheels and running rails, completes the circuit between the traction power network and the train itself. Traction current returns along the running rails and the finite rail to ground conductance implies that earth currents can flow with the possibility of stray currents leaking into ground.

The conductor rail system provides a reliable way of distributing power to a large number of trains in a small geographical area, and gives an aesthetically more pleasing result as well. When in tunnels, a conductor rail allows a smaller structure gauge than would be the case with overhead lines, which can have an impact on the cost of electrification. The major oversimplification in this is the hidden maintenance aspect of tunnel conductor rail.

Network losses
Due to the low supply voltage, the resulting current required to provide sufficient power to the trains is very high. With the major amount of losses within the traction power network associated with $I^2R$, the high current flowing through the network contributes a considerable amount to the electrical losses. However, it should be noted that the overall network impedance is much lower than that of 25kVac network.

Due to the varying location and transient nature of the loads, an overall percentage loss value is difficult to determine. However, through investigations, it has been found that the 750Vdc network has in the region of 1.5 – 2.5 times the electrical losses compared to the 25kVac network.
2.1.2 Operational related systems

In the following a description of operational related systems, to be associated to railway fixed facilities and infrastructures, is included.

Characterization is mainly divided in the following parts:

- Signalling (typically for high and conventional speed)
- Control and Diagnostic communication system

**Signalling subsystem**

*High speed signalling subsystem*

The majority of high-speed signalling subsystems (typically 2x25kV systems) consist of a hierarchical structure branching from a central supervision and control centre further off to the various line side signalling assets (signals, switches, track circuits, etc).

The line field units are therefore centralized to further equipment, which, being not located within the control centre, is normally identified as “peripheral” and typically designated as “Fixed Peripheral Post” (FPP).

Such equipment, which have the function of managing above mentioned line field units, can be located at various positions either within equipment rooms or other dedicated housings (in some systems the terminology Relocatable Equipment Building (REBs) is usual), and, depending on their operational features, can be further divided as follows:

- FPPs used to manage a line section of a given length;
- FPPs used to manage a station and the line sections running thereto, over a total length equivalent to the above fixed value;
- FPPs used to manage crossovers/turnouts always over the same total length equivalent to the above fixed value;
- FPPs used to manage an Interconnection Point with other lines, typically the Conventional ones.

Therefore, on the basis of the above description, the different FPP types manage the same information, but their size and features can vary depending on the number and kind of field units they control and on the area of the line they are placed.

The integrated system supporting the high-speed line railways operations is normally organized in two levels:

- the former level provides for train running supervision and control;
- the latter level includes all of the signalling safety and vital functions and consists of a Static Central Equipment (usually named Vital Control Unit) that controls all the Peripheral Posts.

The connection between the Control Centre and the peripheral service locations is implemented by means of a geographical optic-fibre high-speed network (typically 4 Mbit/s), which makes possible the local operator interfaces management, the diagnostic information distribution and the interface command and control implementation.
Below figure better explains the different hierarchy levels, where meaning of Radio Block Centre is described in the following of the paragraph.

Figure 14: Hierarchy of HS signalling

The part of signalling system which is located at the Control Centre (designated as “Normal Operation System”) is normally duplicated by a back-up System (within the same Control Centre building), which provides a “warm” back-up featuring HW/SW, architectural and configuration characteristics aligned with the same pertinent functions of the “Normal Operation System”. The switching between the Normal Operation System and the back-up System does not normally take place automatically, but following operational procedures and an efficiency verification/maintenance program in order to guarantee the full availability of the back-up functions when necessary.

The High speed Signalling Subsystem generally consists in turn of the following subsystems:

**Line Management Subsystem**

The Line Management Subsystem (LMSS) is the safety signalling system interacting with station and line devices and used to:

- control/command train movements associated with the relevant line section and the yard;
• control/command the individual station devices (field units).

This subsystem particularly performs the safety functions below indicated:

• station logic;
• operator interface management;
• communications between the Radio Block Centre (RBC) and Vital control Unit;
• logic for line and yard safe operations;
• interlocking.

The LMSS is normally implemented by the logic allocated to the Control Centre, which includes the apparatus related to the vital software performing processing and communication of safety functions (Vital Control Unit).

The control and supervision centre provides to:

• send the relevant commands to peripheral posts apparatus, which in turn carry out these commands and performs functions related with area/field device control,
• collect status information from field units and transmitting them in turn to the control centre, for control, command, operator interface and diagnostic purposes;
• implement Local Interface Train Routing (LITR) in those Stations where it is possible to perform local train routing functions.

Software structure normally allows configuration set up without need of any contribution from peripheral apparatus.

Train Spacing Subsystem

The Train Spacing Subsystem (TSSS) guarantees safe control of train running and ensures trains separation depending on:

• the restrictions set by the infrastructure;
• the rolling stock features;
• the line and station equipment conditions managed and communicated by the Line Management Subsystem.

The TSSS is implemented by means of a computer-based system, elaborating messages to be sent to the train on the basis of information received from trackside systems and exchanged with the on-board sub-systems, and designated as Radio Block Centre, as well as with the support from Information Points obtained through the Eurobalises transponders. It typically implements the Level 2 ERTMS European system specifications.

A GSM-Railway radio communication network is typically used for messages exchange between on-board sub-systems and RBC.

The functions performed by RBC logic, can be classified in 5 main categories:

• Functions related to “Train acceptance”;
• Functions related to “Train control command”;
• Functions related to “Train release”;

...
• Functions related to “communication management”;
• Functions related to “diagnostic information transmission”.

Communication Management Subsystem
The Communication Management Subsystem (CMSS) ensures the connection and communication among the different high-speed signalling subsystems. Communication between the Line Management Subsystem and the Train Spacing Subsystem is implemented by means of a internal network at central level, where the safe processors for the Line Management and Train Spacing subsystems are located.

Automation system
It consists of supervision control and command system, which interfaces, at the control centre level, with the Vital Control Unit (VCU) and, by means of such interfacing, receives the signalling information and send the train running commands. All information about the train running are exchanged with the VCU only at control centre level. The equipment of the Diagnostic & Maintenance subsystem in the FPPs are used to interface, for diagnostic and control purposes, all of the subsystems for which remote management has been established.

Summarizing, the automation System, arranged with supervision equipment, is usually dedicated to the following functions:

• Train running
• Electric traction system control
• Diagnostic and maintenance
• Remote supervision/security
• Visual remote inspection

Conventional speed signalling subsystem (≤200km/h)
Conventional speed signalling subsystems are generally characterized by different technical features and physical architectures that can vary in accordance with the different national railway systems.

However, in spite of the existing differences, it is possible to recognize the following common features:

• Fixed Block Signalling system: in order to prevent collision among trains, the railway lines are divided into sections known as “blocks” and trains are not permitted to occupy the same section of track at the same time (only one train is allowed in one block in normal circumstances). This principle forms the basis of most railway safety systems. Conventional railways are mostly characterized by a fixed block signalling system using blocks of fixed length. Recent developments have introduced the “Moving Block” technology that, by means of computer-aided signalling system, is based on the calculation of a ‘safe zone’ around each train; however, the general trend of implementation of this innovative technology is more directed to new mass transit transportation systems than to conventional railways systems.

• Automatic Block-Based Signalling: on the basis of this principle, the access of trains to blocks is based on automatic train detection indicating whether or not a block is clear.
- Presence of Fixed Signals: on most railways, physical signals are placed on lineside in order to indicate to drivers whether or not the line ahead is occupied and to ensure that sufficient space exists between trains.

- Implementation of Safety Systems: in order to avoid human errors (e.g. train driver failure to respond to a signal indication), various auxiliary safety systems are in operation in most conventional railway systems. Generally, they ensure a safe train routing (Interlocking) and require installation of trainborne equipment able to exchange vital information with the track side apparatus (Cab Signalling).

From a general point of view, the main elements constituting a conventional railway signalling subsystem are generally similar to high speed line ones, and they perform similar functions, although differently implemented, as it is described below:

**Line management system:**
The line management system is generally organized in two levels, the first dealing with supervision and control of train operations, the second implementing the safety command and control functions which are concentrated into a Multi station Control Centre (MCC) making it possible to manage the field units by means of a suitable Operator Interface.

This second level system may consist of several MCC subsystems managed by one single operator interface.

**Train spacing system**
Different solutions are normally available for managing the train spacing subsystem:

- **Track Circuits:** it is the most common way to determine whether a section of line is occupied by a train. Each section is controlled by a dedicated track circuit electrically and functionally isolated from the next one. Different typology of track circuits are used throughout the various national railway infrastructures, but the most frequently-used solutions rely on the following common features:
  - Single Rail Track Circuits;
  - Double Rail Track Circuits with insulating joints and impedance bonds;
  - Joint-less Double Rail Track Circuits with tuned circuits.

Moreover, track circuits can also be classified in terms of operating frequency:

- DC Track Circuits;
- AC Low Frequency Track Circuits (<1kHz);
- AC Audio Frequency Track Circuits.
Axle Counters: it is an alternative method of determining the occupied status of a block by using devices located at its beginning and end, counting the number of axles entering and leaving the section. If the number of axles leaving the block is the same of those which have entered it, the block is assumed to be clear.

Communication management subsystem
The Telecommunication Network Infrastructure can typically consist of the following items:

- redundant Gigabit Ethernet backbone on dedicated optic fibre for communication from central to peripheral level, and among adjacent peripheral posts
- redundant Fast Ethernet local networks for the Control Centre and the Peripheral Post
- Other “historic” copper-cabled system (telephone lines, multi core copper cables etc).
Automation system
The supervision, control and command system, similarly to high speed lines, is usually dedicated to the following functions:

- Train operations
- Electric traction system control
- Diagnostic and maintenance
- Visual remote inspection.

Control and Diagnostic communication system
The scope of this paragraph is to describe the communication system criteria and functions related with the Supervisory Control and Data Acquisition System and the Diagnostic & Maintenance System dedicated to traction related subsystems previously described, namely Contact Line System and Traction Power System (TPS).

The description provides the typical features referred to 2x25 kV systems for High Speed System Application, and includes in more detail:

- Traction Power Substations
- Disconnecting stations
- Paralleling stations

Paralleling and Disconnecting Stations can be combined into one only Sectioning Substation.

As far as supervision, control and diagnostic systems for auxiliary subsystems (for example MV/LV power stations of lighting and non-traction power supply systems) are concerned, their description can be found in the following section 2.1.3 in the respective paragraphs.

Contact Line System and TPS: Information flow to the OCC/ECR
According to the Figure below, the events (controls, alarms, status and measurements information) induced by Traction Power and Contact Line Systems are collected at the OCC (Operation Control Centre) or ECR (Electrical Control Room) by:

- SCADA system (control/command functions);
- D&M (Diagnostic & Maintenance System);

by a 2 levels architecture.

The first level has in charge the communication with Peripheral Fixed Site RTU (PFS RTU): the information generated by Contact Line and TPS local equipments are gathered by:

- Host SCADA: it’s located in the technological Rooms (PFS) along the railway by means of a communication protocol (typically IEC60870-5-104)
- Host D&M: similarly to the above item, it’s located in the technological Rooms (PFS) along the railway by means of the same typical protocol
- Historical protocols using software and/or hardware based electronic or electromechanical systems.
Furthermore each RTU is connected to own local supervision system to let to command and to control the peripheral equipment. For modern systems, this connection is made by means IEC60870-5-104 protocol for Contact Line System equipment and by means IEC60870-5-104 protocol for TPS.

The second architecture level has in charge the communication among each PFS and the OCC.

In each PFS is installed both D&M local Server and SCADA server to transfer the gathered information to own central servers located in the OCC by means IEC60870-5-104 protocol.
Figure 16: Contact Line system and TPS information flow to the OCC diagram.
Contact Line System and TPS Functions

The functions of the Contact Line System and TPS are:

- Acquisition and Control Subsystem: performs the function of acquiring remote digital signals and measurements for their pre-processing and transmission to the processing units at a higher level, in addition to the reception of orders of executable commands, and to their execution.

- Local Diagnostic Subsystem: performs the functions of acquisition and processing of information necessary for local diagnostics of the equipment; the necessary information are obtained from the field using simple digital inputs (terminal contacts) or by means serial interface with the protections.

- Remote Control Subsystem: in remote mode, with the selector Excluded/Included, the control is performed directly from SCADA through interfacing with the PT system that will acquire, in parallel, all signals from the field for the logics management.

- Alarms management.

Additionally, the following protection function is associated with TPS:

- Protection Subsystem: performs the function of protection of the lines, automatically opening the switches and circuit breakers in the event of a fault (short circuit, overcurrent, etc.).

Traction Power System interface with external power network

Typically for 25kV and 3kV systems, devices (namely meters and CTs) aimed at allowing accurate billing for power/energy measurement are placed within external power network substation only, whilst those placed within infrastructure substation are limited to internal management purposes. Operational procedures are normally managed by exchange of written instructions, safety being ensured by SCADA at OCC/ECR level. In some cases, especially where the electric provider substation is close to the infrastructure, a copper or fibre optic connection is provided between the two substations, in order to transmit to the electric provider information related with the status of interface equipment useful for substation management, and intertripping signals related with electrical protection for selectivity purpose.
2.1.3 Auxiliary systems

In this section a description of auxiliary subsystems, to be associated to railway fixed facilities and infrastructures, is included.

This characterization is mainly divided in the following parts:

- Heating, Ventilation, Air Conditioning (HVAC) subsystems.
- Point heating subsystems.
- Lighting and non-traction power supply subsystems.

HVAC subsystem

Introduction

The aim of the HVAC subsystem is to ensure proper heating, ventilation and air conditioning to the buildings (stations and in some cases other ancillary buildings part of the railway system), in order to guarantee that the environmental conditions are suitable to allow the operation of all equipment and for passengers and operators comfort.

System architecture

Main HVAC arrangements are foreseen for stations, which normally include:

- Public areas with passengers,
- Operational & maintenance areas with railway staff and equipment.

Further HVAC systems can be present for other outdoor ancillary buildings or shelters which also include operation & maintenance rooms, especially for new lines where HVAC subsystem architecture is similar to the station one due to signalling equipment requirements for air conditioning.

In general, for the comfort of the passengers and the railway staff, the control of both temperature and humidity are recommended, thus requiring both ventilation and air-conditioning system (cooling & heating). However, for the proper operation of electrical equipment, only the control of temperature is required, to exhaust the thermal power load wasted by the equipment, and exhaust radiated solar energy in buildings of lightweight construction; a heating system is required only in some climates for particular items of equipment (i.e. in the UK) to prevent condensation and ensure continual equipment operation. Some equipment may also require the control of humidity.

For new installations, the design of buildings are compliant with current laws and technical standards (locally, nationally or European) on HVAC. The environmental comfort conditions (temperature, humidity, air replacement) for Passengers and Operators and for technical rooms, depending on different seasons situations, are also defined per Environmental laws and technical standards (locally, nationally or European), and, for technical rooms, also by the requirement of the operation of the equipment as instructed by the manufacturer. Older buildings, particularly brick-built, may contain only heaters which are controlled by fixed thermostats.

The typical thermal power loads can be classified as follows:

- The heat transmitted from and to the external environment;
• Lighting system heating;
• Heat dissipated by people;
• Public areas equipment heating;
• Operational & maintenance areas equipment heating.

The typical HVAC plants can be classified as follows:

• Ventilation plants for public areas and operational & maintenance areas air replacement;
• Air cooling plant for public areas and operational & maintenance areas;
• Air heating plant for public areas and operational & maintenance areas;
• Direct expansion cooling and heating heat pumps for small areas or rooms.

Usually, a dedicated ventilation system is installed in UPS and Generator rooms; the system is controlled by HVAC equipment on-board microprocessor or by PLCs. Furthermore, generally, sensors are installed inside stations for the acquisition for temperature and humidity monitoring

HVAC subsystem also includes an air conditioning system that could affect the reliability and availability of the rail system, since the absence of proper refrigeration of operational-related equipment (like signalling) could cause improper operation of the railway system.

Typically, the HVAC subsystem includes HVAC power & control cabinets fed by a single or three phase low voltage power line.

If the HVAC subsystems are used for technical rooms with vital equipment, it could be necessary to install an emergency power supply system involving UPS (for control function) and/or Diesel power generator (for power function).

In the following figures, some typical block diagrams of the HVAC subsystem are shown; in red line the electric power flow is indicated, in blue line the thermal one.
Figure 17: Typical HVAC chiller system (block diagram).
Figure 18: Typical HVAC direct expansion cooling system (block diagram).
Figure 19: Typical HVAC ventilation system (block diagram).
**Supervision and control system**

Where installed, the HVAC commands and controls from and to the OCC/ECR are managed by the SCADA subsystem; this includes certain HVAC diagnostic and maintenance data.

At sites where HVAC SCADA indications and controls are available, equipment is interfaced to a SCADA Host (RTUs and PLCs), that collects the commands and indications and transmits the data to the OCC, typically by a fibre network (TCP/IP or dedicated protocol) or via a 3rd party telephone exchange.

The typical communication protocols between the HVAC equipment and the RTUs are MODBUS or RS485 and sometimes dry contact relays.

The typical controls, sent from HVAC equipment to OCC, are:

- HVAC system on or off
- HVAC system fault
- HVAC system in manual/remote
- Temperature and humidity of the rooms managed by HVAC

The typical commands, sent from OCC to HVAC equipment, are:

- HVAC system on or off (in many cases this function may be omitted to conserve energy)

In any case, the HVAC subsystem could be managed locally, typically for maintenance activity.

**Point Heaters Subsystem**

**Introduction**

The performance and safety of the railway systems can be affected if particular areas of track, such as turnouts, are involved in snowfall and/or atmospheric phenomena that may cause the risk of formation of ice. For these reasons, and where these conditions are envisaged, a heating system of points is utilized, with the goal of avoiding dangerous conditions and to limit the disruption during adverse weather conditions.

If this system is important for the traditional railway network it becomes even more essential for high-speed network.

**System architecture**

In most cases, the power required for points heating is achieved by connecting heating system control cabinets to the main low voltage switchboard (MLVS) downstream the auxiliary MV/LV transformers, or from a local external power supply. A heating system, usually consists of:

- MLVS providing power for the distribution board;
- LV line feeder 400Vac or 230Vac;
- distribution board/panel from where the individual power supplies for each transformer are taken;
- transformers (possible typical solutions are 400/50Vac or 230/110Vac);
• LV line feeder (possible typical voltages are 50Vac or 110Vac, but other values can also be found) to supply power for the heating of point elements
• heating elements, accessories and fixings.

The subsystem of heating points is typically composed of the functional blocks as described by the diagram below.

---

Supervision and control system

To allow the system to operate automatically, each control cabinet contains a weather conditions control and detection unit, which automatically handles the start-up and shutdown according to conditions that detect falling or likely to fall snow or icy temperatures, through suitable sensors of temperature humidity and/or precipitation.

The management of point heating performed through the Control Cabinet generally consists of:

• data processing and control unit, located in the distribution board;
• weather detectors/sensors;
• track sensors (to be installed below the points at the identified track sections).

The apparatus is schematically constituted by a control and detection unit attached to an array of different sensors, which may include all or some of the following depending on the different systems and applications:
• humidity sensor
• environmental temperature sensor
• rail temperature sensor in each zone
• precipitation sensor

As described above, the control and detection unit is fit in order to allow sensors data processing and system automatic management and operation.

Typically above described remote control is performed by a data transmission achieved through a PLC/modem installed in the control unit and a typical MODBUS communication protocol.

Lighting and non-traction power supply subsystem

Introduction

The definition of lighting and non-traction power supply is mainly referred in this paragraph to all the power supply subsystems put in place in order to feed all the electrical loads and services not directly related with traction, and consequently including, in general, either operational or auxiliary loads, as defined by the classification given in this document. Such power supply subsystems usually feed:

• Signalling & Telecoms equipment placed in station buildings or wayside;
• Station equipment loads (e.g. lighting, HVAC);
• Depot equipment loads;
• Tunnel wayside equipment;
• Other operational/auxiliary equipment.

System architecture

The subsystem is generally fed by the medium voltage upstream network (typically 11kV/15kV/33kV 50/60Hz) or in other situations by a local DNO, in low voltage, at either 3-phase or 1-phase, 400/230 Vac. The medium voltage switchgear is fit in order to ensure a suitable distribution to downstream MV network, and normally includes (non exhaustive list):

• Incoming (from medium voltage network) cubicle;
• Measurement unit cubicle;
• Interconnection cubicles ( to adjacent stations/buildings)
• Transformers protection cubicle.

This last cubicle is aimed to feed MV/LV transformers (typically with secondary nominal voltage of 400V). The transformers supply energy to the Main Low Voltage Switchboard (MLVS) which is fit in order to provide a suitable distribution to all low voltage loads.

A further emergency/back-up supply is expected to feed the General Low Voltage Switchgear in case of fault of the upstream MV network or of the transformers, for some loads which for their function require power supply also in such circumstance. Usually diesel generators (DG) are installed in this case to feed the loads of the individual stations/buildings. For other loads, which cannot allow the short power interruption during DG start-up, another continuity supply (also
identified as no-break), in combination with a UPS, is installed. Only in some systems the emergency supply from a DG is also provided to MV level via a further transformer, in order to feed, via the internal MV ring, the loads belonging to different locations. Additional electrical distributions can be present at further voltage levels (e.g. 1 kV tunnel dorsal for lighting and power supply) in other systems.

The general functional diagram of lighting and non-traction power supply subsystem shown below represent in a schematic way the typical features, but it should be taken into account that many systems can be different especially when referring to the choice of low voltage distribution levels and the emergency/back-up supplies schemes/criteria.

**Figure 21: Lighting and non-traction power supply subsystem general functional diagram.**

The main components of the lighting and non-traction power supply subsystem, relevant for overall railway system energy consumption are summarized below:

- Medium voltage switchboards;
- Operators panel boards;
- UPS;
- Diesel generators;
- Low voltage switchboards;
- Lighting cables/accessories.
Supervision and control system

The supervision system for Medium Voltage equipment acquires signals coming from the MV/LV equipment of the LPS plant and performs control/command functions in relation to the same equipment.

In particular, its main functionalities are:

- Diagnostic of devices in the MV/LV switchgear locations and network infrastructure
- Command of the entities in the MV/LV switchgear locations
- Start up of procedures for MV power supply reconfiguration (where foreseen), making possible a system reconfiguration (automatic or manual) following a fault to ensure that all the loads are powered.

The main devices of the automation system are PLC (Programmable Logic Controller), Concentrators (Front & End), Servers and Supervision Stations (Client).

Each MV/LV switchgear location will generally have its own PLC. For commands and state condition indications activation, the PLCs are connected with two units Central Front/End normally placed at the essential points of a section of the MV network/ring (typically positions related with the adjacent incoming feeds from upstream MV network or other locations); in fact, there is a communication between the MV/LV PLCs and the Concentrators Front/End via an optical fibre communication network.

The concentrators (front & end) are connected, via LAN network, to the servers where all the MV information is collected and provided.

Concentrators front/end and servers manage the hot stand-by, therefore, a data alignment is foreseen either between the concentrators front/end or between the servers.

The supervision stations (Client), via LAN network, communicate with the server to refresh all the data and information and to issue commands.

In addition, the servers communicate with the OCC for data transfer and in the OCC normally two servers and supervision stations are present.

A typical communication protocol used to exchange data between the various components of the supervision system is IEC60870-5-104.

A general architecture scheme can be found below:
Figure 22: Supervision system for non-traction power supply subsystem diagram, (not part of the traction SCADA system).

2.1.4 Reference documents and standards for fixed facilities and infrastructures

<table>
<thead>
<tr>
<th>Number</th>
<th>Title</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 50119</td>
<td>Railway applications - Fixed installations - Electrical traction overhead contact lines</td>
<td>31/01/2010</td>
</tr>
<tr>
<td>EN 50121-1</td>
<td>Railway applications. Electromagnetic compatibility. General</td>
<td>31/08/2006</td>
</tr>
<tr>
<td>EN 50121-2</td>
<td>Railway applications - Electromagnetic compatibility - Part 2: Emission of the whole railway system to the outside world</td>
<td></td>
</tr>
<tr>
<td>EN 50121-5</td>
<td>Emission and immunity of fixed power supply installations and apparatus</td>
<td>29/09/2006</td>
</tr>
<tr>
<td>EN 50122-1</td>
<td>Railway applications - Fixed installations - Part 1: Protective provisions relating to electrical safety and earthing</td>
<td>15/05/1998</td>
</tr>
<tr>
<td>EN 50122-2</td>
<td>Railway applications - Fixed installations - Part 2: Protective provisions against the effects of stray currents caused by DC traction systems</td>
<td>15/05/1999</td>
</tr>
<tr>
<td>EN 50123-1</td>
<td>Railway applications. Fixed installations. DC switchgear. General</td>
<td>11/07/2003</td>
</tr>
<tr>
<td>EN 50123-2</td>
<td>Railway applications. Fixed installations. DC switchgear. DC circuit breakers</td>
<td>11/07/2003</td>
</tr>
<tr>
<td>EN 50123-7-1</td>
<td>Railway applications. Fixed installations. DC switchgear. Measurement, control and protection devices for specific use in DC traction systems. Application guide</td>
<td>15/07/2003</td>
</tr>
<tr>
<td>EN 50124-1</td>
<td>Railway applications. Insulation coordination. Basic requirements. Clearances and creepage distances for all electrical and electronic equipment</td>
<td>15/05/2001</td>
</tr>
<tr>
<td>EN 50124-2</td>
<td>Railway applications - Insulation coordination - Part 2: Overvoltages and related protection</td>
<td>15/05/2001</td>
</tr>
<tr>
<td>EN 50125-2</td>
<td>Railway applications. Environmental conditions for equipment. Fixed electrical installations</td>
<td>19/03/2003</td>
</tr>
<tr>
<td>EN 50126-1</td>
<td>Railway applications. The specification and demonstration of reliability, availability, maintainability and safety (RAMS). Basic requirements and generic process</td>
<td>15/12/1999</td>
</tr>
<tr>
<td>EN 50152-1</td>
<td>Railway applications. Fixed installations. Particular requirements for AC switchgear. Single-phase circuit-breakers with Un above 1 kV</td>
<td>30/04/2008</td>
</tr>
<tr>
<td>EN 50152-2</td>
<td>Railway applications. Fixed installations. Particular requirements for AC switchgear. Single-phase disconnectors, earthing switches and switches with Un above 1 kV</td>
<td>30/04/2008</td>
</tr>
<tr>
<td>EN 50152-1</td>
<td>Railway applications - Fixed installations - Particular requirements for alternating current switchgear - Part 1: Circuit-breakers with nominal voltage above 1 kV</td>
<td>30/11/2012</td>
</tr>
<tr>
<td>EN 50152-2</td>
<td>Railway applications - Fixed installations - Particular requirements for alternating current switchgear - Part 2: Disconnectors, earthing switches and switches with nominal voltage above 1 kV</td>
<td>01/07/2008</td>
</tr>
<tr>
<td>EN 50162</td>
<td>Protection against corrosion by stray current from direct current systems</td>
<td>19/01/2005</td>
</tr>
<tr>
<td>EN 50163</td>
<td>Railway applications. Supply voltages of traction systems</td>
<td>06/01/2005</td>
</tr>
<tr>
<td>Standard Code</td>
<td>Description</td>
<td>Date</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>EN 50180</td>
<td>Bushings above 1 kV up to 36 kV and from 250 A to 3,15 kA for liquid filled transformers</td>
<td>15/08/1999</td>
</tr>
<tr>
<td>EN 50327</td>
<td>Railway applications - Fixed installations - Harmonization of the rated values for converter groups and type tests on the converter groups</td>
<td>01/03/2003</td>
</tr>
<tr>
<td>EN 50328</td>
<td>Railway applications - Fixed installations - Electronic power converters for substations</td>
<td>01/09/2003</td>
</tr>
<tr>
<td>EN 50329</td>
<td>Railway applications. Fixed installations. Traction transformers</td>
<td>28/07/2003</td>
</tr>
<tr>
<td>EN 50345 (2nd)</td>
<td>Railway applications - Electromagnetic compatibility - Part 2: Emission of the whole railway system to the outside world</td>
<td>2009</td>
</tr>
<tr>
<td>EN 50388</td>
<td>Railway applications - Power supply and rolling stock - Technical criteria for the coordination between power supply (substation) and rolling stock to achieve interoperability</td>
<td>27/09/2005</td>
</tr>
<tr>
<td>EN 60076-1</td>
<td>Power transformers. General</td>
<td>15/09/1997</td>
</tr>
<tr>
<td>EN 60255-1</td>
<td>Measuring relays and protection equipment. Common requirements</td>
<td>28/02/2010</td>
</tr>
<tr>
<td>BS EN 60265-1</td>
<td>Specification for high-voltage switches. Switches for rated voltages above 1 kV and less than 52 kV</td>
<td>15/06/1998</td>
</tr>
<tr>
<td>IEC 60265-1</td>
<td>Specification for high-voltage switches. Switches for rated voltages above 1 kV and less than 52 kV</td>
<td>15/06/1998</td>
</tr>
<tr>
<td>EN 61140</td>
<td>Protection against electric shock. Common aspects for installation and equipment</td>
<td>24/06/2002</td>
</tr>
<tr>
<td>IEC 61140</td>
<td>Protection against electric shock. Common aspects for installation and equipment</td>
<td>24/06/2002</td>
</tr>
<tr>
<td>EN 61325</td>
<td>Insulators for overhead lines with a nominal voltage above 1000 V. Ceramic or glass insulator units for DC systems. Definitions, test methods and acceptance criteria</td>
<td>15/02/1996</td>
</tr>
<tr>
<td>IEC 61325</td>
<td>Insulators for overhead lines with a nominal voltage above 1000 V. Ceramic or glass insulator units for DC systems. Definitions, test methods and acceptance criteria</td>
<td>15/02/1996</td>
</tr>
<tr>
<td>EN 61508-1</td>
<td>Functional safety of electrical/electronic/programmable electronic safety-related systems. General requirements</td>
<td>30/06/2010</td>
</tr>
<tr>
<td>EN 61952</td>
<td>Insulators for overhead lines. Composite line post insulators for AC systems with a nominal voltage greater than 1000V. Definitions, test methods and acceptance criteria</td>
<td>31/03/2009</td>
</tr>
<tr>
<td>EN 62271-200</td>
<td>High-voltage switchgear and control gear. AC metalenclosed switchgear and control gear for rated voltages above 1 kV and up to and including 52 kV</td>
<td>31/10/2005</td>
</tr>
<tr>
<td>EN 62271-1</td>
<td>High-voltage switchgear and control gear. Common specifications</td>
<td>31/03/2009</td>
</tr>
</tbody>
</table>
2.2 ROLLING STOCK SUBSYSTEMS

Rolling stock subsystem can be classified as follows:

1. Traction power related and power supply systems.
2. Operational related systems.
3. Auxiliary systems.

2.2.1 Traction power related and power supply systems

Traction subsystems for Vline = 1500 Vdc

The traction system for a line voltage at 1500 Vdc consists of the following main sections:

- High voltage stage;
- Inverter;
- Braking chopper;
- Traction motors;
- TCU

The figure below represents an in-principle block diagram for a traction system at 1500 Vdc.

![Figure 23: Typical traction block diagram for V line = 1500 Vdc](image)
**TCU parameters for motors’ speed and voltage regulation**

Some important parameters managed by TCU are reported in the following table.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Origin</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>F ref</td>
<td>Effort reference</td>
<td>Drive console/CCU</td>
<td>MVB</td>
</tr>
<tr>
<td>V line</td>
<td>Line voltage</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>I line</td>
<td>Line current</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>V f</td>
<td>Filter voltage</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>Open/Close Cont</td>
<td>Signals to open and close contactors</td>
<td>HV contactors</td>
<td>Cables</td>
</tr>
<tr>
<td>ON/OFF INV</td>
<td>On/off pulses for inverter IGBT</td>
<td>Control board in TCU</td>
<td>Optical fiber</td>
</tr>
<tr>
<td>ON/OFF CH</td>
<td>On/off pulses for braking chopper IGBT</td>
<td>Control board in TCU</td>
<td>Optical fiber</td>
</tr>
<tr>
<td>Vrs, Vst, Vtr</td>
<td>Output inverter voltages</td>
<td>From inverter transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>Ir, Is, It</td>
<td>Output inverter currents</td>
<td>From inverter transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>T sensors MOT 1</td>
<td>Temperature sensors motor 1</td>
<td>From stator</td>
<td>Cables</td>
</tr>
<tr>
<td>T sensors MOT 2</td>
<td>Temperature sensors motor 2</td>
<td>From stator</td>
<td>Cables</td>
</tr>
<tr>
<td>Pick-up 1</td>
<td>Rpm on motor 1</td>
<td>Motor axle</td>
<td>Cables</td>
</tr>
<tr>
<td>Pick-up 2</td>
<td>Rpm on motor 2</td>
<td>Motor axle</td>
<td>Cables</td>
</tr>
<tr>
<td>Tr</td>
<td>Rheostat Temperature</td>
<td>From rheostat</td>
<td>Cables</td>
</tr>
</tbody>
</table>

**High voltage stage**

The high voltage stage includes the following components:

- Pantograph;
- Line voltage and current transducers;
- High voltage discharger;
- Harmonics detector at 50 Hz;
- Line filter inductance, circuit Breaker, contactors.

The line filter (common to the inverter and chopper section) is generally a single cell LC designed for a thermal current around 200 ÷ 300 A.

The input voltage range for a high voltage stage under $V_{line} = 1500\ \text{Vdc}$ is $1000 \div 1800\ \text{Vdc}$. 

---

MRL-WP1-D-ANS-013-06  Page 67 of 145  03/12/2013
Inverter
The inverter is connected in upstream to the DC supply line (nominal value equal to 1500 Vdc) and it carries out the function of feeding and control of three-phase asynchronous traction motors.

The inverter is generally realized by IGBT valves with typical rated characteristics of about 3300V/1200A.

A series of electrical transducers detects in real time the voltage and current input and output values of the converter and, together with the thermal transducers (thermocouples) and tachogenerators (pick up) signals, allows the TCU:

- to regulate the power of the motors by means of appropriate modulation PWM (pulse width modulation) techniques; and
- to manage the necessary protections.

Thus, the inverter typically drives the AC motors with a variable frequency and voltage regulation.

Typical electrical values for an inverter operating under V line = 1500 Vdc are reported below:

**Input Inverter electrical data**

<table>
<thead>
<tr>
<th>Input</th>
<th>Continuous voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage range:</td>
<td>1000 ÷ 1800 Vdc</td>
</tr>
</tbody>
</table>

**Output Inverter electrical data**

<table>
<thead>
<tr>
<th>Output</th>
<th>Sinusoidal ac three-phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage range:</td>
<td>800÷1400 V</td>
</tr>
<tr>
<td>Power range:</td>
<td>500÷800 kW</td>
</tr>
</tbody>
</table>

**Braking chopper**

The braking chopper is a step-down chopper and it is designed for operation with a nominal voltage of 1500 Vdc. It manages the dissipation of the not recoverable braking energy. Typical electrical values are reported below:

**Chopper electrical data**

<table>
<thead>
<tr>
<th>Input</th>
<th>Continuous voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage range:</td>
<td>1000 ÷ 1800 Vdc</td>
</tr>
<tr>
<td>Power range:</td>
<td>500 ÷ 1000 kVA</td>
</tr>
</tbody>
</table>

**Traction motor**

In the following, typical electrical values for a traction motor are reported:

<table>
<thead>
<tr>
<th>Type</th>
<th>asynchronous three-phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage range:</td>
<td>800 ÷ 1200 V</td>
</tr>
</tbody>
</table>
Power range 100 ÷ 200 kW
Type of supply by inverter

**TCU**
The main aim of the Traction Control Unit is to control and manage the traction power converter.

The TCU performs the following functions:

- receives the commands to be executed;
- generates the waveforms required for controlling the power converter;
- detects any malfunctions of the power circuits and control and performs the appropriate protections;
- transmits to the central control unit (CCU) of vehicle the diagnostic information about the operating status and/or faults events;
- transmits to an external unit digital and analogue signals for advanced diagnostics purpose.

The figure below represents a typical electric diagram of a traction converter.

![Figure 24: Typical traction system electrical diagram for 1500 Vdc](image)

**Remote measurements**
Many railway vehicles have the capability to perform measurement of the global vehicle’s energy consumption. This is possible by using voltage and current transducers of high accuracy.

The voltage and current signals are sent to an EMT (energy meter), which processes the data and calculates the power and the energy absorbed in a certain time interval. The processed signals are
then usually sent to a unit that stores the data. These can also be displayed locally on an LCD monitor placed on the driver's desk. These information can also be sent through GSM/GPRS communication systems.

In the figure below a typical Energy Meter system is represented.

![Energy Meter Diagram](image)

**Figure 25: Typical energy meter diagram**

The measuring system is designed in compliance to rolling stock standards (EN 50121 1-2-3, EN 50125-1, EN 50155). In particular it is in compliance to final draft of the CENELEC-TC9X working group 11 (Railway applications – Energy metering on-board trains) and CENELEC prEN 50463.

**Traction subsystems for V line = 3000 Vdc**

This traction system consists of:

- High voltage stage;
- Two-phase Chopper;
- Braking chopper;
- Inverter;
- Traction motors;
- TCU.

The figure below shows a typical traction system’s block diagram.
**Figure 26: Typical traction system block diagram for 3000 Vdc**

**TCU parameters for motors’ speed and voltage regulation**

Some important parameters managed by TCU are reported in the following table.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Origin</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>F ref</td>
<td>Effort reference</td>
<td>Drive console/CCU</td>
<td>MVB</td>
</tr>
<tr>
<td>V line</td>
<td>Line voltage</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>I line</td>
<td>Line current</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>V dc-link</td>
<td>DC-link Voltage</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>Open/Close Cont</td>
<td>Signals to open and close contactors</td>
<td>HV contactors</td>
<td>Cables</td>
</tr>
<tr>
<td>ON/OFF INV</td>
<td>On/off pulses for inverter IGBT</td>
<td>Control board in TCU</td>
<td>Optical fiber</td>
</tr>
<tr>
<td>ON/OFF CH</td>
<td>On/off pulses for chopper IGBT</td>
<td>Control board in TCU</td>
<td>Optical fiber</td>
</tr>
<tr>
<td>ON/OFF Bch</td>
<td>On/off pulses for braking chopper IGBT</td>
<td>Control board in TCU</td>
<td>Optical fiber</td>
</tr>
<tr>
<td>Vrs, Vst, Vtr</td>
<td>Output inverter voltages</td>
<td>From inverter transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>Ir, Is, It</td>
<td>Output inverter currents</td>
<td>From inverter transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>----------</td>
<td>--------------------------</td>
<td>--------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>T sensors MOT 1</td>
<td>Temperature sensors motor 1</td>
<td>From stator</td>
<td>Cables</td>
</tr>
<tr>
<td>T sensors MOT 2</td>
<td>Temperature sensors motor 2</td>
<td>From stator</td>
<td>Cables</td>
</tr>
<tr>
<td>Pick-up 1</td>
<td>Rpm on motor 1</td>
<td>Motor axle</td>
<td>Cables</td>
</tr>
<tr>
<td>Pick-up 2</td>
<td>Rpm on motor 2</td>
<td>Motor axle</td>
<td>Cables</td>
</tr>
<tr>
<td>Tr</td>
<td>Rheostat Temperature</td>
<td>From rheostat</td>
<td>Cables</td>
</tr>
</tbody>
</table>

**High voltage stage**
The high voltage stage includes the following components:

- Pantograph
- Line voltage transducer
- High voltage discharger
- Harmonics detector at 50 Hz
- Circuit Breaker

**Typical Electrical characteristics**
Typical electrical values for a high voltage stage under V line = 3000 Vcc are reported below:

**Input voltage range:** 1000 ÷ 4000 Vdc

**Current range:** 1500 ÷ 2000 A

**Two phase chopper**
The two-phase chopper is a step down reversible chopper which produces a stabilized continuous voltage to supply the inverters; the reversibility allows to recover the braking energy on the 3kV dc feeding line.

**Electrical characteristics**
Typical electrical values for a two phase chopper under V line = 3000 Vcc are reported below:

**Input voltage range:** 1000 ÷ 4000 Vdc

**Output voltage range:** 1800 ÷ 2400 Vdc

**Output current range (maximum value):** 800 ÷ 1000 A

**Braking chopper**
The braking chopper is used for dissipating the non-recoverable braking energy by means of braking resistors.

Typical electrical values for a braking chopper for Vline = 3000 V are reported below:
Electrical characteristics
Voltage range: 3600 - 4000 Vdc
Braking resistance at 20 °C: 2 x 3÷4Ω
Current range (maximum value): 600÷700 A
Rheostat power (maximum value): 2 x 700÷750 kW

Inverter
The inverter is fed by the two-phase chopper, through the DC link. The in-principle structure and control logics of this type of inverter are similar to the previously described 1500 Vdc traction inverter (pag. 68).

Typical electrical values for a 3 kV dc traction inverter are reported below:

Electrical characteristics
Input voltage: 1800÷2400 Vdc
Output voltage range( 1° harmonic r.m.s. value): 0 ÷ 1800 Vac
Output current range (maximum value): 600 ÷ 800 A
Power range (maximum value): 1800 ÷ 2100 kVA

Traction motor
The inverter generally supplies a set of traction motors. Typical traction motor electrical values are reported in the next table:

Electrical parameters
Type three-phase asynchronous
Voltage range (1° harmonic rms value) 900 ÷ 1500 V
Continuous 1° harmonic current (rms value) 140 ÷ 160 A
Traction power range (maximum value at motor axle): 350 ÷ 400 kW
Braking power range (maximum value at motor axle): 400 ÷ 450 kW

TCU
As already described for 1500 Vdc traction systems, the main aim of the Traction Control Unit is to control and manage the power converter. In addition, the TCU performs the following functions:

- generate the pulses ON/OFF required for controlling the two phase chopper;
- detect malfunctions of the power circuits and implement the appropriate protections

The figure below represents a typical electrical diagram for traction system with Vline = 3000 Vdc.
Remote measurements
The same considerations introduced for 1500 V dc traction system are also applicable for 3000 V dc traction system. Moreover the measurement of vehicle’s energy consumption is possible to be managed both in local and in remote modality via GSM/GPRS or Wi-Fi.

Traction subsystems for Vline = 15 kV- 16,67 Hz
This traction system’s architecture typically consists of:

- Power Transformer;
- Traction Converters (which include the 4Q-Converter, dc-link and the traction inverter);
- Traction motors;
- TCU.

The figure below shows a typical block diagram of a traction sub-system.
Figure 28: Typical block diagram for 15 kV – 16 2/3 Hz traction system

**TCU parameters for motors’ speed and voltage regulation**

Some important parameters managed by TCU are reported in the following table.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Origin</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>F rif</td>
<td>Effort reference</td>
<td>Drive console/CCU</td>
<td>MVB</td>
</tr>
<tr>
<td>V line</td>
<td>Line voltage</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>I line</td>
<td>Line current</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>Open/Close Cont</td>
<td>Signals to open and close contactors</td>
<td>HV contactors</td>
<td>Cables</td>
</tr>
<tr>
<td>ON/OFF INV</td>
<td>On/off pulses for inverter IGBT</td>
<td>Control board in TCU</td>
<td>Optical fiber</td>
</tr>
<tr>
<td>ON/OFF 4Q</td>
<td>On/off pulses for 4Q IGBT</td>
<td>Control board in TCU</td>
<td>Optical fiber</td>
</tr>
<tr>
<td>Transformer parameters</td>
<td>Temperature transformer, On/off oil pump</td>
<td>Control board in TCU</td>
<td>Cables</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------------------------------------</td>
<td>----------------------</td>
<td>--------</td>
</tr>
<tr>
<td>V dc-link</td>
<td>Voltage between the 4Q and inverter</td>
<td>From dc-link voltage transducers</td>
<td>Cables</td>
</tr>
<tr>
<td>Vrs, Vst, Vtr</td>
<td>Output inverter voltages</td>
<td>From inverter transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>Ir, Is, It</td>
<td>Output inverter currents</td>
<td>From inverter transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>T sensors MOT 1</td>
<td>Temperature sensors motor 1</td>
<td>From stator</td>
<td>Cables</td>
</tr>
<tr>
<td>T sensors MOT 2</td>
<td>Temperature sensors motor 2</td>
<td>From stator</td>
<td>Cables</td>
</tr>
<tr>
<td>Pick-up 1</td>
<td>Rpm on motor 1</td>
<td>Motor axle</td>
<td>Cables</td>
</tr>
<tr>
<td>Pick-up 2</td>
<td>Rpm on motor 2</td>
<td>Motor axle</td>
<td>Cables</td>
</tr>
</tbody>
</table>

*Main transformer for 15 kV- 16,67 Hz*

The main transformer is designed for adjusting the line voltage level to an acceptable value for the input section of the 4Q traction converter.
Electrical characteristics

With reference to the above figure, general typical electrical values for a 15 kV – 16.6 Hz main transformer are reported below:

Nominal frequency: 16,667 Hz

Primary winding (T1)

Continuous power range at maximum ambient temperature: 1000 ÷ 1200 kVA

Rated voltage: 15 kV

Traction secondary windings (T2 ÷ T5)

Continuous power range: 200 ÷ 250 kVA

Nominal no load voltage range: 800 ÷ 1000 V

Nominal 1st harmonic current range (rms. value): 250 ÷ 300 A
4Q Converter
The 4Q converter is generally constituted by “four quadrant rectifiers”, purposely adopted to recover the braking energy to the traction line.

Electrical characteristics
Voltage range (non permanent voltage) 10500 ÷ 18000 V
Supply voltage rated frequency (range variation) 16,67 Hz (16,33÷17Hz)

Inverter stage
The second stage of the traction converter mainly consist of an inverter (controlled by the traction control unit) that supply power to the set of traction motors.

Electrical characteristics
The typical max power range at the motor shaft of the inverter is 600 ÷ 700 kW

Traction motor

Electrical characteristics
The typical electrical values for a traction motor are reported below:

Continuous power range: 300 ÷ 400 kW
Rated voltage range: 900 ÷ 1200 Vac
Rated current range 200 ÷ 250 A
Maximum speed range 3800 ÷ 4000 rpm

TCU
As already described for the 1500 Vdc and 3000 Vdc traction systems, the main aim of the Traction Control Unit is to control and manage the power converter. In addition the TCU performs the following functions:

• generate the pulses ON/OFF required for controlling the 4Q Converter;
• detect malfunctions of the power circuits and implement the appropriate protections;
• control the main transformer parameters.

Remote measurements
The same considerations introduced for 3000 Vdc traction system are also applicable for 15 kV – 16,67 Hz traction systems.
Multi-Voltage traction subsystems for high speed operation (Vline = 25 kV – 50 Hz, 3 kV dc, 1.5 kV dc)

This traction system is a multi-voltage system. It can work for a line voltage in alternate current (25 kV – 50 Hz) and in direct current (3 kV and 1.5 kV). This type of traction system is generally implemented for high speed trains suitable for multi-voltage operation (interoperability). The in-principle architecture consists in the following 4 main sections:

- Power Transformer;
- Traction Converter (each one includes a 4Q-Converter and a traction inverter);
- Traction motors set;
- TCU.

In the following figure, a typical block diagram for this type of traction subsystem is provided.
TCU parameters for motors’ speed and voltage regulation

With reference to the above reported block diagram, the main parameters managed by TCU are summarized in the following table.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Origin</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>F rif</td>
<td>Effort reference</td>
<td>Drive console/CCU</td>
<td>MVB</td>
</tr>
<tr>
<td>V line in DC</td>
<td>DC Line voltage</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>V line in AC</td>
<td>AC Line voltage</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>I line in DC</td>
<td>DC Line current</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>I line in AC</td>
<td>AC Line current</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>V dc-link</td>
<td>DC Voltage between the 2Q/4Q and inverter</td>
<td>From HV transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>Open/Close Contactors</td>
<td>Signals to open and close contactors</td>
<td>HV contactors</td>
<td>Cables</td>
</tr>
<tr>
<td>ON/OFF 2Q/4Q</td>
<td>On/off pulses for 2Q/4Q IGBT</td>
<td>Control board in TCU</td>
<td>Optical fiber</td>
</tr>
<tr>
<td>ON/OFF INV</td>
<td>On/off pulses for inverter IGBT</td>
<td>Control board in TCU</td>
<td>Optical fiber</td>
</tr>
<tr>
<td>Transformer parameters</td>
<td>Temperature transformer, On/off oil pump</td>
<td>Control board in TCU</td>
<td>Cables</td>
</tr>
<tr>
<td>Vrs, Vst, Vtr</td>
<td>Output inverter voltages</td>
<td>From inverter transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>Ir, Is, It</td>
<td>Output inverter currents</td>
<td>From inverter transducers panel</td>
<td>Cables</td>
</tr>
<tr>
<td>T sensors MOT 1-2-3-4</td>
<td>Temperature sensors from motor 1-2-3-4</td>
<td>From stator</td>
<td>Cables</td>
</tr>
<tr>
<td>Pick-up 1-2-3-4</td>
<td>Rpm on motor 1-2-3-4</td>
<td>Motor axle</td>
<td>Cables</td>
</tr>
</tbody>
</table>

Power transformer

In case of AC supply, the power transformer is used for adjusting the line voltage to the rated voltage level of the traction converters. Typically the primary supply voltage is 25 kV, 50Hz.
Traction converter

The traction converter drives a set of traction motors and its typical architecture can be summarized as follows:

- First conversion stage typically constituted by a 4Q DC/DC converter (not in operation in case of DC 1.5 kV supply);
- Second conversion stage typically constituted by a traction inverter;
- Braking chopper for dissipating non-recoverable braking energy.

Figure 31 Typical traction diagram for multi-voltage traction systems

TCU

As previously described, the main aim of the Traction Control Unit is to control and manage the traction converter, the braking chopper and their cooling system.

Traction motor

Generally, the in-principle architecture depicted in the figures above is applicable for high speed service (up to 260 km/h). For very high speed vehicles (over 300 km/h) or whenever requested by train performances, this architecture can be doubled in order to adequately supply the traction motor set. The following figure shows a typical traction system architecture for very high speed trains.
Figure 32: Typical traction system block diagram for a very high speed locomotive (over 300 km/h)

The typical characteristics of a traction motor for high speed service (up to 260 km/h) are reported below.

Type: three-phase asynchronous
Voltage range: 1700 ÷ 1900 V
1st harmonic r.m.s.
Power range: 300 ÷ 350 kW
Rated current range: 120 ÷ 130 A 1st harmonic r.m.s.
Maximum frequency: 150 Hz

The typical characteristics of a traction motor for very high speed service (over 300 km/h) are reported below.

Type: three-phase asynchronous
Voltage range (maximum value in square wave): 1700 ÷ 1900 V
Rating power: 1000 ÷ 1200 kW
Rating current: 380 ÷ 420 A

Remote measurements
The same considerations introduced for 1500 Vdc traction system are also applicable for this traction systems.
2.2.2 Operational related systems

On-board system control architecture

The train control system (TCS) is a microprocessor-based system that is specifically designed for on-board railway environment.

The system is structured in functional subsystems interconnected through a overall communication network compliant with the IEC 61375 standard (Train Communication Network).

In accordance with the aforementioned standard, the communication network can be organized in two separate communication systems:

- vehicle bus that interconnects the main control units inside the vehicle (e.g. MVB, Multifunctional Vehicle Bus);
- train bus which allows communication between vehicles/locomotives operating in multiple cars configuration (e.g. WTB, Wire Train Bus).

A train control system architecture is depicted in the following figure.

![Figure 33: Block diagram for train control system](image)

Referring to the above in-principle figure, the train control system functions can be organized in the following subsystems, interconnected via the MVB bus:

- Gateway (GTW);
- Vehicle’s Central Control Unit (CCU);
- Integrated Diagnostic Unit (IDU);
- Traction Control Unit (TCU);
- Remote Interface Units (RIO);
- Auxiliary converter’s control unit (GS);
- Signalling and data transmission systems (DIS, ETCS, GSM-R).

**GTW**

The GTW equipment realizes the communication node (gateway) between the train bus and the vehicle bus and it is able to manage the train communication network (TCN) by implementing the suitable media access rules among the components of TCN (e.g: train bus as Master or Slave, vehicle bus as Administrator Bus; etc.).
**CCU**
The CCU represents the core of the train control system. It operates the supervision, the control and the command of the main trains parameters related to train dynamics (e.g. traction, coasting and braking motion regimes) and related to the other operating functions of the vehicle (e.g. doors opening/closing, auxiliary converters control, etc.), for different train set configuration (single or multiple locomotives).

**IDU**
Diagnostic system main aim is to support the personnel working on trains during driving and maintenance activities. The diagnostic system can also interface via the train bus with other cars diagnostic systems to collect other diagnostic data.

The display of diagnostic information is carried out through the integrated diagnostic unit (IDU) on the control console. In addition, the IDU can display the status of the locomotive/vehicle key components. Through the same IDU it is also possible to exclude parts of the traction and auxiliary converters.

**TCU**
The traction control unit is specifically designed for the supervision, control and command of a traction converter according to the train dynamic profile set by the driver. Thus the TCU implements the functions of command and control of electromechanical equipment of the traction converter, and of protection of the power converter components.

**RIO**
It is a local control unit which allows basic SW to run for Input/Output signals acquisition.

**GS**
The Auxiliary converter’s control unit performs the control and the protection functions for the auxiliary power converter.

**Signalling and data transmission system**
The signalling and data transmission system aims to collect, route and manage signalling data and other vehicle on-board information. In the following, key sub-systems for on-board signalling and data transmission are briefly described.

**DIS**
The DIS (Driver Information System) is a distributed system that aims to manage data collected on board and to route them to the Driver. Typically the on-board DIS collect, store and automatically send data to a central elaboration unit.

**ETCS**
The ETCS (European Train Control System) is a signalling control and train protection system designed to ensure interoperable signalling systems on the European railway network. It is related to safety issue concerning the management of the train on the European railway network, especially on high-speed lines.
GSM-R
Vehicles can be equipped with GSM-R system for vehicle-to-wayside communications according to EIRENE specifications, the system generally consists of a GSM radio unit receiver/transmitter (located in a proper rack), a user interface (at the control console), and a GSM antenna (located on the roof).

Typically, the GSM-R system is also used for vehicle-to-vehicle communications, according to UIC 568.

On-board system control interfaces
The main interfaces of the train control system can be realized by means of the following communications protocols:

- MVB;
- Ethernet (TCP/IP);
- Controller Area Network (CAN-Bus);
- RS485.

The TCS also controls the electromechanical equipment through direct signals:

- Digital signals (low voltage supply);
- Analogue signals.

The following figure shows a typical diagram of the TCS interfaces with other on-board equipments.

![Figure 34: TCS interfaces with on-board units (by different communication bus).](image-url)
Passengers information system

The passenger information and display system (PIS) is an information system which provides real-time and off-line passenger information (e.g. predictions about arrival and departure times, information about the nature and causes of disruptions, etc.). Typically the PIS consists of the following sub-systems:

- Visual information sub-system;
- Audio sub-system;
- Communication sub-system.

Visual information sub-system

Typically, the visual information sub-system consists of displays and monitors, both in-board or outside the vehicle, showing off-line and real-time route and travel information. In general, all information are processed by the vehicle on-board computer and sent to displays and to monitors through a proper communication system.

Audio sub-system

The audio sub-system main aim is to set-up and stream audio announcement, according to visual information. Typically the audio sub-system communicates with the vehicle on-board computer and to the central announcement database for audio data retrieval. The audio unit uses audio data fragments to set-up individual announcements and streams them digitally to in-board and outside vehicle loudspeakers.

Communication system

The communication sub-system manages PIS data and information, routing them to the proper sub-system or equipment. Typically, an Ethernet network is used for in-vehicle communication, while for vehicle-to-station communications data can be routed on WLAN or GPRS networks.
2.2.3 Auxiliary systems

Usually auxiliary systems encompass the following items:

- Command circuits system;
- Heating Ventilation and Air Conditioning (HVAC) system;
- Lighting system;
- Cooling system for power electronics;
- Battery charger system;
- Pneumatic system.

In the following a brief description of each item is reported.

Command circuits system

It is mainly constituted by contactors and relays and its main purpose is to control and command vehicle’s power circuits.

Heating Ventilation and Air Conditioning (HVAC) system

The main scope of the HVAC system is to control temperature and relative humidity inside each train’s car. Generally the HVAC system is constituted by multiple mono-block air treatment units, usually installed on the roof of each car, operating independently.

This unit is typically composed by:

- a refrigeration and dehumidification section for air cooling;
- an air heating section;
- an air flow control section, including fans and ventilation system.

The system is also equipped with sensors for command, control, diagnosis and protection of the entire system. In addition, it encompasses dedicated interfaces for set-up and for maintenance purposes. Therefore the HVAC, through its own control and regulation system, automatically manages the train's internal temperature and relative humidity.

Control and communication interfaces

HVAC interfaces with other on-board equipment are realized through logic signals or via different communication systems such as MVB-EMD (refer to EN 61375-1) or RS485.

Power supply interfaces

As depicted in the following figure, the HVAC system can be interfaced with the low voltage and/or the medium voltage power network of the vehicle for feeding purpose.
Figure 35: Typical block diagram for HVAC system interfaces

Typical HVAC's technical data in a 1500kV dc vehicle is summarized below.

**Compressor section**

- Power input: 10 ÷ 15 kW

**Air flow control section**

- Air flow rate: 7400 m³/h
- Power input: 1,5 ÷ 2 kW

**Condensing section**

- Air flow rate: 20000 m³/h
- Power input: 0.8 ÷ 1 kW

**Air heating section**

- Total power supply: 10 ÷ 11 kW

**Lighting system**

The lighting system ensures the suitable illumination level in the passengers cars through the use of fluorescent bulbs or led lights.

**Cooling system for power electronics**

Generally static power converters require a suitable cooling systems (e.g. air forced or water cooling), in order to ensure over-temperature control and a suitable heat dissipation.
Battery charger system
In order to ensure power supply to train’s essential loads in case of power outage, the vehicle is equipped with on-board energy storage systems (typically electrochemical batteries). The battery charger system main aim is to provide energy to the batteries, in order to maintain the suitable state of charge as well as to feed essential loads during normal operation.

Following, the typical 3 kV dc train battery charger main features are reported.

<table>
<thead>
<tr>
<th>Battery typology</th>
<th>Nickel-cadmium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>190 ÷ 200 Ah</td>
</tr>
<tr>
<td>Power</td>
<td>9 ÷ 10 kW</td>
</tr>
</tbody>
</table>

Pneumatic system
Pneumatic system mainly provides compressed-air supply for train operation. Following, of the main pneumatic systems functions are summarized:

- traction circuit command;
- mechanical braking;
- pantograph operation powering;
- doors operation powering.

Auxiliary converters overview
Typically, the above described items are fed by dedicated auxiliary power supply converters. In this section a general overview of such type of converted is briefly introduced. Moreover, in the following figure a representation of the most frequently-adopted architectures is reported.
Figure 36: Most frequently-used auxiliary converters architectures
Typical auxiliary converter electrical characteristic for vehicles operating at 1500 Vdc

<table>
<thead>
<tr>
<th>Input section</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage operating range</td>
<td>500 V – 2000 V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output section</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>380 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz ± 1%</td>
</tr>
<tr>
<td>Typical rated power</td>
<td>60 – 70 kVA</td>
</tr>
</tbody>
</table>

Table 6: Electrical characteristic of an auxiliary converter for vehicles operating at 1500 Vdc

Typical auxiliary converter electrical characteristic for vehicles operating at 3000 Vdc

<table>
<thead>
<tr>
<th>Input section</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage operating range</td>
<td>1800 V – 4000 V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output section</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>380 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz ± 1%</td>
</tr>
<tr>
<td>Typical rated power</td>
<td>200 – 250 kVA</td>
</tr>
</tbody>
</table>

Table 7: Electrical characteristics of an auxiliary converter for vehicles operating at 3000 Vdc
Typical auxiliary converter electrical characteristics for freight locomotives operating at 3000 Vdc

<table>
<thead>
<tr>
<th>Input section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage operating range</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Typical rated power</td>
</tr>
</tbody>
</table>

Table 8: Electrical characteristics of an auxiliary converter for freight locomotives operating at 3000 Vdc

Typical auxiliary converter electrical characteristics for high speed vehicles operating in multi-voltage traction subsystem (25 kV – 50 Hz, 3 kV dc, 1,5 kV dc)

<table>
<thead>
<tr>
<th>Input section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage operating range</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Typical rated power</td>
</tr>
</tbody>
</table>

Table 9: Electrical characteristics of an auxiliary converter for high speed vehicles operating in multi-voltage traction subsystem (25 kV ac – 50 Hz, 3 kV dc, 1,5 KV dc)
**Typical auxiliary converter electrical characteristic for passengers coaches**

<table>
<thead>
<tr>
<th>Input section</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage operating range</td>
<td>1900 V – 4200 V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output section</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>380 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz ± 1%</td>
</tr>
<tr>
<td>Typical rated power</td>
<td>35 – 36 kVA</td>
</tr>
</tbody>
</table>

**Table 10: Electrical characteristics of an auxiliary converter for passengers coaches**
### 2.2.4 Referenced documents and standards for rolling stocks

<table>
<thead>
<tr>
<th>Document/Norm</th>
<th>Title/Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 50163</td>
<td>Railway applications – Supply voltages of traction systems</td>
</tr>
<tr>
<td>EN 50124 (series)</td>
<td>Railway applications – Insulation coordination</td>
</tr>
<tr>
<td>EN 50125 (series)</td>
<td>Railway applications – Environmental conditions for equipment</td>
</tr>
<tr>
<td>EN 50126</td>
<td>Railway applications – The specification and demonstration of dependability, reliability, maintainability and safety (RAMS)</td>
</tr>
<tr>
<td>EN 50206-1</td>
<td>Railway applications – Rolling Stock – Part 1: Pantographs for main line vehicles; characteristics and tests</td>
</tr>
<tr>
<td>CEI EN 50207</td>
<td>Railway Applications – Electric power converters for rolling stock</td>
</tr>
<tr>
<td>CEI EN 50155</td>
<td>Railway Applications – Electric equipment used on rolling stock</td>
</tr>
<tr>
<td>EN 50153</td>
<td>Railway Applications – Rolling stock. Protective provisions relating to electrical hazards</td>
</tr>
<tr>
<td>CEI EN 60310</td>
<td>Railway Applications – Traction transformers and inductors on board rolling stock</td>
</tr>
<tr>
<td>EN 60529</td>
<td>Degrees of protection provided by enclosures (IP Code)</td>
</tr>
<tr>
<td>CEI EN 61373</td>
<td>Rolling Stock equipments – Shock and vibrations tests</td>
</tr>
<tr>
<td>CEI EN 61377-3</td>
<td>Railway Applications – Rolling stock. Combined testing of alternating current motors, fed by an indirect converter, and their control system</td>
</tr>
<tr>
<td>CEI EN 61881</td>
<td>Rolling Stock equipments – Capacitors for power electronics</td>
</tr>
<tr>
<td>CEI EN 61287-1</td>
<td>Railway Applications – Power converter installed on board rolling stock – Characteristics and test methods</td>
</tr>
<tr>
<td>CEI 20-17</td>
<td>Fire retardant rubber insulated cables with low emission of smokes and toxic and corrosive gases for train, trams and alike</td>
</tr>
<tr>
<td>CEI UNEL -736</td>
<td>Railways rolling stock fire retardant cables with low emission of smokes and toxic corrosive gases, rubber insulated</td>
</tr>
<tr>
<td>EN 129</td>
<td>Railway Applications: Safety related electronic systems for signaling</td>
</tr>
<tr>
<td>EN 50121-1</td>
<td>Railway applications – Electromagnetic Compatibility – Part 1: General</td>
</tr>
<tr>
<td>EN 50121-2</td>
<td>Railway applications – Electromagnetic Compatibility – Part 2: Emission of the Whole Railway System to the Outside World</td>
</tr>
<tr>
<td>EN 50121-3-1</td>
<td>Railway applications – Electromagnetic Compatibility – Part 3-1: Rolling</td>
</tr>
<tr>
<td>Standard/IEC</td>
<td>Description</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>EN 50121-3-2</td>
<td>Railway applications – Electromagnetic Compatibility – Part 3-2: Rolling Stock – Apparatus</td>
</tr>
<tr>
<td>EN 50121-4</td>
<td>Railway applications – Electromagnetic Compatibility – Part 4: Emission and Immunity of the Signalling and Telecommunications Apparatus</td>
</tr>
<tr>
<td>EN 61375-1</td>
<td>Electronic railway equipment. Train communication network (TCN) – Part1: General architecture.</td>
</tr>
<tr>
<td>IEC 62052-11</td>
<td>Electricity metering equipment (AC) – General requirements</td>
</tr>
<tr>
<td>IEC 62053-21</td>
<td>Electricity metering equipment (AC) – Particular requirements</td>
</tr>
<tr>
<td>EN 50463 1-2-3-4-5</td>
<td>Railway applications – Energy meters for Railway Rolling Stock</td>
</tr>
</tbody>
</table>
3. TECHNOLOGY SOLUTION FOR RAILWAY SYSTEMS

This section is focused on the identification and description of different technology solutions (such as reversible sub-stations, energy storage systems, local energy sources for each element and sub-system previously defined. This section does not detail non-technical solutions, such as those associated with the driving of the train or control of the signals.

3.1 REVERSIBLE TRACTION SUBSTATIONS

The use of regenerating braking functionality is one of the most important methods that allow energy savings in a railway transportation system. It can be partly used for on-board consumption (auxiliaries and comfort functions) and the remaining part of energy is fed back into the traction supply line (catenary or 3rd rail).

The possibility of an effective re-use of such regenerated energy is mainly dependent on the two following technical aspects:

- The receptivity of the traction system that is mainly related to the possibility of other trains to pick up the regenerated energy for acceleration purposes. It can ensure a more effective use of the traction energy internally to the rail system without any involvement of other external entities (external power supply network). On the other hand, this characteristic is depending on traffic density, headways and voltage drops on the traction supply line. It should be noted, however, that a receptivity optimization for energy saving purposes can be achieved through better planning and handling of train operations;

- Use of Reversible Traction Substations: this provides the capability of feeding the train regenerative braking energy (up to 100%) to the external power distribution network, whilst maintaining the exchange of energy among trains on the traction supply line. The system receptivity is improved by feeding the excess of regenerative braking energy to the upstream network and this improvement is more effective in railway systems that are characterized by a low value of system receptivity. In addition, further benefits are related to the minimization of line and distribution losses as well as to the balancing of the paralleled substations' loads in order to optimize energy flow.

In the next paragraphs the concept of reversible substation is outlined with particular emphasis on the most feasible and commonly-recognizable solutions that can be summarized as follows:

1. DC Systems: reversible electric substations for DC traction networks;

2. AC Systems that can be split in the 2 following sub categories:
   a. AC Traction systems with the same operating frequency of the external power supply network (50Hz);
   b. AC Traction systems operating at different frequency of the external power supply network (e.g. 15 kV 16.67Hz traction systems).

With reference to the AC systems, only the 2.b. category has been dealt in the next pages because of it represents a more interesting scenario in term of system architecture.

In fact, the 50 Hz Traction systems has an inherently reversible capability and examples relevant to such scenarios are reported in § 4.2.4.
3.1.1 Reversible electric substation and controllable power conversion equipment for DC traction networks.

Conventional DC traction substations don’t support capability of regenerating energy outside the DC network because the diode rectifiers only allow unidirectional flow of power. Therefore, in this case, the excess of regenerated energy is generally dissipated by using braking resistors in order to prevent the DC bus voltage from rising above the trip level.

The components of the converter

The objectives of a reversible DC substation are to regenerate up to over 99% of the braking energy, allowing the removal of on-board braking resistors, realizing dynamic power balance between adjacent substations and compensate for dynamic fluctuations of primary voltage. It should also control overloads, meet relevant standards for total harmonic distortion (THD) and finally, it should be able to compensate for the reactive power which is generated to ensure it is not wasted.

The figure below presents the architecture of a typical power converter.

![Figure 37: Structure of a reversible power converter.](image)

**Structure of the reversible power converter**

In simple terms, if a bi-directional inverter is added to the diode rectifier the power flow of the substation then can be reversed. The inverter is then only activated when recovered energy is available. This can be detected by a voltage rise at the substation. The minimum voltage limit should be controlled in such a way that priority for the regenerated energy is given to allow other trains, to allow them to accelerate. If no other train is close enough, the energy is fed by the inverter into the supply grid. An issue arises by the use of a diode rectifier (standard on most DC railways), whereby the output voltage can be combined with dynamic fluctuations of the input voltage, causing a voltage raise. In this case, the inverter will be (wastefully) recycling the energy provided by the rectifier. To avoid this problem, a thyristor-controlled rectifier can be introduced which maintains the output voltage at the nominal value. This type of converter, consisting of a controlled rectifier and an inverter connected in opposite electrical orientations, can also include...
harmonic compensation, control-command and fault monitoring technologies. Its application can cover power supply voltages between 750 Vdc and 3000 Vdc for power ranging from 600 kW to 5.4 MW.

**Power electronic control (PEC)**
The converter is controlled by a power electronic control unit that generates the pulses controlling a IGBT bridge and the thyristor bridge. The PEC also allows voltage and current regulation and the bridges’ protection. It provides both active filter and inverter functions to the IGBT bridge. It sets the sequencing and can provide auxiliary functions (ventilation, water unit, etc.) It insures that the inverter and rectifier operating modes will not overlap to avoid recycling power (the inverter feeding back the energy provided by the rectifier). In addition to that, in order to regenerate as much as possible of the braking energy, the difference between the maximum braking voltage at the traction unit and the minimum voltage at the substation, from which the regeneration mode starts, should be as large as possible in order to compensate for the voltage drop caused by losses along the transmission lines and within the contact system. This can be realized by a voltage regulation which provides an expanded energy recovery voltage range.

**Substation load balancing**
As mentioned before, the converter can regulate the output voltage on the DC side (750 Vdc -5% to 10% depending on the load, which can vary from 0 to 150% of the rated power). It can also dynamically regulate each substation’s load in both traction and regenerating phases. This load regulation helps limiting the overload in each substation. This load balancing allows a better current distribution in both normal and degraded operation, thereby minimizing losses and overloads.

**ON/OFF switching**
The converters’ operation is normally autonomous, with automatic configurations/reconfigurations, and isolation in case of fault. The converter is normally equipped with an event recorder providing history log of the faults and sequences. A summary of the faults, On/Off statuses, load statuses can be available locally and for transmission to the OCC/ECR via the SCADA optic fibre network or towards the outside world via internet.
3.1.2 Reversible frequency converters for 15 kV 16.67 Hz traction systems

In such typology of traction systems the possibility of feeding the excess of regenerative braking energy to the upstream power network is directly related to the bi-directional capability of frequency converters deployed in the traction substations.

Frequency converters overview

Generally speaking, it is possible to recognize 4 different types of frequency converters:

1. Rotary frequency converters;
2. Cycloconverters;
3. DC-Link converters; and
4. Multilevel Converters.

Rotary frequency converter

The basic structure of a rotary converter is consisting of 3-phases 50 Hz asynchronous motor and a synchronous 16,67 Hz generator. These 2 apparatus are mechanically connected by a common shaft in order to transform frequency from 50 Hz to 16 ⅔ Hz.

A transformer on the secondary side of the converter is necessary to adapt the traction side to 16.5 kV.

Rotary frequency converter are typically realized by a railway vehicle’s assembly consisting of:

- a trailer containing the transformer and the control system;
- a trailer containing the motor and the generator.
Cycloconverters

Figure 39: In-principle structure of a Cycloconverter

A cyclo-converter is a frequency converter and the frequency transformation is realized through a particular topological arrangement of the thyristor bridges.

In particular, as depicted in the following figure, this frequency converters rely on a basic configuration realized by 2 thyristor bridges connected in a anti-parallel configuration.

Figure 40: Basic thyristor configuration for a Cycloconverter

The control of the output frequency on the 16.67 Hz side is realized by the adoption of opportune algorithms for controlling the delay angles ($\alpha$) of each thyristor bridges.

The typical power rating for such type of converter usually spans from 13 to 15 MVA.
DC-Link converters

A DC-link converter is a frequency converter where the frequency transformation occurs via a DC-link architecture.

These devices consist of a 50 Hz rectifier bridge producing direct current which is then inverted to produce AC of 16 ⅔ Hz. Transformers are also included on both AC input and output circuitry in order to changes voltage levels and number of phases.

The PWM is the most common modulation adopted for controlling these type of converters.

Typical rating power is 15 MVA.
Multi Level DC-Link converters

Figure 42: In-principle structures of Multi Level DC-Link converters

It represent a new solution for static converters that consists of a cyclo-converter with several IGBT modules connected in series in order to achieve to the required output voltage level.
Overview of main energy-related basic facts for frequency converters

<table>
<thead>
<tr>
<th>Type of Frequency Converter</th>
<th>Achievable Efficiency</th>
<th>Reversibility</th>
<th>Other Characteristics</th>
</tr>
</thead>
</table>
| Rotary frequency converter  | From 88% to 93 %;     | Yes           | • high overload capability;  
|                             |                       |               | • necessity of synchronization with the 50 Hz grid before entering into normal service;  
|                             |                       |               | • lower possibility of control than the static converters |
| Cycloconverters             | It can reach 96-97%   | Yes           | • almost instantaneous synchronization with the power distribution network;  
|                             |                       |               | • Output voltage presents big harmonic contents;  
|                             |                       |               | • low overload capability; |
| DC-Link converters          | It can 97-98%; (Only modern DC-Link Converters) | Yes           | • Control of voltage angle and voltage level in order to balance the active and reactive power flows between substations for losses reduction purpose;  
|                             |                       |               | • almost instantaneous synchronization with the power distribution network |
| Multi Level DC-Link converters | It can reach 98.5 %; | Yes           | • negligible harmonic content in the output voltage;  
|                              |                       |               | • the redundant architecture ensures high level of service availability allowing normal operation even in case of one faulted module per branch. |

Table 11: Main basic facts for frequency converters
Energy optimization opportunities for frequency converters

The following measures can be put in place in order to enhance an energy-optimized management of 15kV 16.67Hz traction systems:

- Voltage magnitude and phase control in order to:
  - minimize power losses along the traction network;
  - optimize the load sharing among converter substations;
- Automatic frequency converter switch-on/switch-off control system in order to keep into operation only the optimal number of frequency converters;
- Optimized management of the traction power consumed and regenerated by the vehicles can be achieved by adopting a Traffic Optimization system.
3.2 ENERGY STORAGE SYSTEMS

In reference to transportation systems, the idea is to store the kinetic energy of the vehicle during the braking phase, and to use it during the acceleration phase. This principle implies:

- The possibility of regenerative braking;
- The implementation of energy storage systems on-board or lineside (e.g. in the substations);
- The use of real power converters as interface between the energy storage system and the load (traction line or vehicle power-train).

In the following, different energy storage devices suitable for the railway system will be presented.

In general, a storage system consists of one or more modules connected in series and/or in parallel, which are then interfaced with a static power converter. The power flows during charge and discharge are delegated to the static converter. Such a converter is typically a buck-boost type chopper that provides a connection between the network power (high voltage side) and storage devices (low-side), controlling the power flow in each direction by the use of suitable algorithms. Therefore, the use of converters has a dual function:

- To control and manage the power flow, to and from the network, in relation to the requirements of the load,
- To harmonize the voltage level of the storage modules to that required by the loads.

Generally, the storage system may be installed in either of two locations:

- storage systems installed on board the vehicle,
- storage systems installed in the substation and/or along the line.

The first solution is particularly advantageous with reference to energy recovery and is more effective than locating the storage system in the substation or in a point of the line. This is because the accumulation systems located on board realize an immediate and direct electrical connection with the drive propulsion. This clearly allows recovery of most of the kinetic energy available assuming that there are minimal losses along the contact line within the train, which is not the case if the accumulation is undertaken in the substation or along the line. It’s important to note, however, that the utilization of energy recovered in an on-board storage system is limited to that particular train. Other advantages, however, make this type of system potentially most attractive. The possibility of being able to perform catenary- or 3rd rail-free operations for several hundred meters is another advantage. Consider, for example, a loss of supply where the train is standing in a tunnel, or requiring to cross a particular junction which is not electrified. A further advantage is that it is independent from traffic conditions of the network, because the energy exchange takes place continuously in line with the point of contact between the same line and the pantograph or shoegea. We can thus summarize the advantages of this solution as:

- increase of the efficiency of the entire system,
- ability to overcome short sections not supplied (for example allowing for entering station platform in case of failure).

The main disadvantage is the installation on-board the vehicle, due to the small suitable spaces that are present on existing cars. One solution might be to place the storage system in place of the
banks of braking resistors. Another aspect to consider is the significant increase of the weight of the car with consequent increased demand for energy for its movement.

As regards the installation of the storage systems in substation or along the line, their interval along the route can make a decisive contribution to reducing the voltage drops along the line and the partial recovery of energy in the line at the systemic level, i.e. not only the individual vehicle, as well as the optimization of the energy exchanges between the different trains. The use of storage systems, properly distributed along the urban and/or suburban railway, may be a viable technical solution which contributes decisively to the improvement of the overall performance of the trains’ drive system and the rationalization of consumption through an increased energy recovery.

The use of storage systems in substation and/or along the contact line, therefore, allows the avoidance of dissipative deceleration; to recover part of the kinetic energy of braking, fulfilling the function of auxiliary power supply in support of the contact line. This is reflected in a positive manner on the electrical energy distribution since it places a lower demand of power on the electric power substation and an improvement of the voltage levels in the line feeder, with the consequent reduction in voltage drop across the network during acceleration and braking of trains, which would usually occur on lines which run trains with frequent stopping patterns. A further advantage of placing the solution on the ground is the lack of strict constraints in terms of weight and bulk, which is particularly relevant when considering fitment to existing trains. The benefits on the net power arising from the use of systems of accumulation along the line are multiple:

- reduction of line losses owing to a more sustained line voltage,
- leveling power consumption in the substation,
- possibilities of increasing the frequency of vehicles per hour,
- potential of using better performing vehicles,
- reduction of the voltage drops in line with consequent improvement of the voltage profile at the pantograph or shoegear of the vehicle,
- improved efficiency of power conversion of the entire drive system (drives on board, airline, primary power substation),
- increase the distance between substations to distribution lines of new construction.

### 3.2.1 Mechanical energy storage systems

A flywheel is a mechanical accumulator which stores kinetic energy, which can then be transformed into electrical energy if it is connected to an electric generator.

Magnetic suspensions often are used to reduce frictions, which are caused by the high rotation speed.

The kinetic energy is stored during braking of the vehicle and used as electric energy during the acceleration phase.
Naturally, each energy storage system is characterized by different functionality and also by different advantages and disadvantages; below a list of the flywheel characteristics:

Main advantages:

- their performance is independent from changes in ambient temperature,
- they don’t have toxic components,
- they can perform continuous charge/discharge cycles without loss of performance (because the yield does not depend on the state of charge),
- high yield of each cycle (97-98%).

Main disadvantages:

- when the rotation speed is very high it is necessary to use magnetic bearings,
- because of the connection with the electric machine, thermal limits must be respected,
- it’s necessary to use a mechanical protection & containment system in case of explosion of the system,
- the gyroscopic effect can be dangerous for the balance of a moving vehicle.

### 3.2.2 Electric and electrochemical ESS

**Electrochemical energy storage systems (Batteries)**

There are many important existing applications of electrochemical accumulators in applications of both small loads and large loads. Examples of loads supplied by electrochemical accumulators are:

- small electromechanical appliances,
- home electronic devices (mobile phones, laptop computers, etc.).
- Applications of high energy including:
  - auxiliary power supply to motor vehicles, aircraft, ships,
  - supply the propulsion of submarines,
  - supply the propulsion of electric or hybrid road vehicles,
  - power reserve of telephone exchanges,
- power reserve of power plants,
- Uninterruptible Power Supply (UPS).

A typical structure of a battery is shown in the following figure:

![Figure 44: Example of an electrochemical battery.](image)

**Supercapacitors**

A supercapacitor is a particular storage system, with better characteristics than a normal capacitor, such as:

- higher stored Energy,
- lower weight,
- more efficiency.

The stored energy is higher compared to a classic capacitor because the charge separation occurs in a double layer electrode at distances of molecular scale.

The larger supercapacitors, currently, can reach values of capacity of 5000 F, whilst the highest energy density reached is 30 [Wh/kg]. Although such value of energy density is lower than the one achievable by lithium batteries, it should be noted that their major advantage, if compared with a battery, is the power density considerably higher, a feature that makes them at the present essential devices used as accumulators of energy in the short term in the power electronics.

The cell of a supercapacitor is constituted basically by two electrodes, a separator and an electrolyte. Each of the two electrodes is formed by a metallic collector, which is the part that presents high conductance, and by an active substrate, which is the part that presents a very large surface area, typically hundreds of thousands of times greater than the armor of a smooth conventional capacitor of the same size. The two electrodes are separated by a membrane, the separator plate, which allows the mobility of the ions electrolytic and at the same time prevents the conduction of electrons. The flat cell thus formed is rolled up or folded, making them assume a cylindrical shape or rectangular, and then is stored in a container. Subsequently, the system is impregnated by an electrolyte, which can be of the solid type or in organic solution or aqueous, depending on the power required by the application, as will be seen below.

Ultracapacitors have capacity well in excess of normal capacitors, and unlike batteries do not have any chemical reaction during the process of accumulation or release of energy which allows them to be able to withstand a high number of charge-discharge cycles.
The electrodes are coated with very porous carbon substances and the dielectric classic between the surfaces is replaced with electrolytic substances. The high porosity determines a surface area equivalent large and applying a potential difference is created a movement of negative and positive charges to the surface respectively positive and negative. They have very high capacity, of the order of hundreds of Farads [F], thanks to the high surface area of the electrodes and the minimum distance between the charges.

The working voltage of the supercapacitor is determined by the decomposition voltage of the electrolyte and depends on the temperature, intensity of current and the duration of life of the device request. Considering the next relationship, which expresses the capacity of a capacitor:

\[ C = \varepsilon \frac{A}{d} \]

where:

- \( \varepsilon \) is the dielectric constant of the insulating medium absolute,
- \( A \) is the surface area of the electrodes at which the charges are concentrated,
- \( d \) is the distance between the armature.

It is immediately realized that the capability of such a supercapacitor is very high, thanks to the thin distance that separates the opposite charges at the interfaces between electrodes and electrolyte, but above all thanks to the enormous surface area of porous electrodes.

An innovative kind of supercapacitor is the Lithium Ion Condenser (LIC), is characterized by an electrode with particles of Lithium Ion that has a higher electric potential than the electrode of a classic supercapacitor.
3.3 LOCAL ENERGY SOURCES

A new concept of energy source is focused on the concept of Distributed Energy Resources (DER); the idea is to have various energy generators located in the grid, or better in a smart grid.

The main aim is to integrate the energy sources in the electric infrastructure, and to allow the automatic control and the interaction between the different sources.

Most people are aware of the rising cost of energy and the necessity for a policy of energy efficiency; in the last years the use of renewable energy sources has increased, and in civil, industrial and transportation infrastructures, both the following the innovative technologies have been used:

1. photovoltaic panels;
2. wind generators.

3.3.1 Photovoltaic panels

The photovoltaic panel is a component capable of generating electricity when sunlight is projected onto it.

Today the performance of the panels is at most equal to 15%.

The topology of a PV system is subdivided into two categories:

- stand alone,
- grid connected.

In the first one the system is isolated from the grid and this mode is used when it is difficult to connect to the network. The energy produced is stored in electric accumulators and it is used when it is necessary.

The electric power is DC ; inverters are used to convert it into alternating current.

![Figure 45: Stand Alone configuration for photovoltaic panels.](image)

In the second solution, the grid connected one, the photovoltaic plant is connected to the electric grid and when the whole plant works in overproduction the energy from the PV is dispatched in the grid; in this case the energy dispatched is paid.

If the PV plant can’t satisfy the energy request the energy is taken from the electric grid.
In this case it isn’t necessary the use of energy storage systems, because there is a continuous energy exchange; although there is clearly a requirement to include a DC/AC converter to obtain alternate current energy.

Figure 46: Grid connected configuration for photovoltaic panels.

3.3.2 Wind generators

In a wind power plant, the electric energy is produced by exploiting the wind speed.

The common term for a device which harnesses energy in the wind for electrical transformation is wind turbine. It has blades that rotate in the presence of wind; they rotate if the wind has a minimum speed (cut-in wind speed). The blades (which constitute the wind turbine rotor) are connected to a transmission shaft, which is connected to a gearbox and, finally, to the electric generator.

The gearbox allows an increase in the rotation speed of the blades in order for the generator to produce a greater amount of electricity as the wind speed increases.

If the energy is provided in DC it’s necessary to use an inverter.

The blades rotation speed has a maximum pre-set value, beyond which the electric energy production is not increased; this protection system is used to avoid excessive mechanical stresses.

There are two kinds of wind turbine that can be used:

- horizontal axis;
- vertical axis.

The horizontal axis wind turbine have blades with horizontal rotation axis; the typical powers vary from hundreds of Watts to 3MW

They may have more blades, and if the number of blades grows the speed of rotation decreases and the yield increases.

A smaller number of blades increases the noise but decreases the wind turbine price.

In vertical axis wind turbine the blades rotate independently from the wind direction, because they have their entire surface exposed to wind. They are used in places in which the speed of the wind is variable. They are characterized by low noise and ease of maintenance.
The problems in the use of renewable energy sources are related to:

- the difficulty to forecast the real energy supply;
- the power quality;
- sometimes, the too long payback time.

On the first point, renewable energy sources do not provide energy continuously but are characterized by a discontinuous operation. This is often because the primary energy is not available.

It’s therefore necessary to create complex forecasting models.

Regarding the bad quality of the energy, all the renewable energy sources produce electric energy in Direct Current (DC); the grid, in general, works in Alternate Current (AC) and so it’s necessary to use power electronic converters to transform the electric DC energy in AC energy.

A power electronic converter, such as an inverter or a rectifier, imparts a high harmonic content onto the grid, which can disrupt the correct function of other electrical and electronic machinery.

So, to reduce the harmonics effect it’s necessary to use filters.

Regarding to the third point, the use of generators from renewable sources often requires high investment costs; in an investment, one of the parameters to evaluate is the payback time, that is the return time (days, months, years) of the financial investments.

Sometimes public institutions provide financing for people who install renewable sources plants, which reduces the payback time and so encourages private individuals to install these innovative systems in their own homes.

When there aren’t the incentives, the payback time increases and it is often not deemed economical to install and use renewable sources plants.
4. NON-ELECTRICAL CONSTRAINTS AND INTERFACES, LEGISLATION, PROCEDURES

This chapter is aimed to cover the identification, description and characterization of those key non-electrical constrains, both internal and external to the Railway system, and of those interfaces affecting energy consumption and management. Such constraints would include aspects connected with legislation, energy supply and consumption contractual commitments, and possible control procedures.

This section analyses regulatory requirements as well as specific agreements being applied, and identifies functions, products and parties involved in non-electrical constrains.

In order to collect existing data available from the consortium members, a proper questionnaire have been developed and submitted to infrastructure managers/operators to retrieve required data. The questionnaire structure has been defined in order to highlight the following topics for each member state/country:

1. Legal Constraints (definition of standard/legal frame)
   This section is aimed to identify the standards and legislations that apply to the relationship between railway and electricity infrastructure in different countries, with reference to distribution of electricity.

2. Contractual relationship between energy suppliers and railways, including definition of real practice/procedures:
   This section is expected to identify and highlight the following:
   - Procedures and/or frameworks to regulate the provision of energy to railways.
   - Billing payment criteria to energy provider
     - By real measures
       - Using energy meters installed within sub-stations
       - Using on-board meters
     - By fixed tariff per kilometer run by the train
     - By consumption forecasts
     - By breakdown of overall energy consumption
     - By other criteria
   - Kind/level of standardization for the energy meters
   - Main present issues/problems related with standardization/calibration of energy meters
   - Details about possible energy flow back from the railways network to the external power network, and about possible compensations for the regenerated energy
   - Possible technologies for energy storage/regeneration used or planned to be introduced
4.1 LEGAL CONSTRAINTS

In the European railway sector, these non-electrical constrictions are exposed in the Directives, Decisions and Regulations related to railway. All these legal instruments are published in the Official Journal of the European Union and in the ERA website.

At national level, specific commitments may apply.

A Directive is a legislative act of the European Union, which requires Member States to achieve a particular result in a fixed period of time. Member States are required to make changes to their laws (commonly referred to as “transposition”) in order for the directive to be implemented correctly.

A Decision is a legal instrument available to the European institutions for the implementation of European policies. Decisions are binding acts which may have general application or may apply to a specific addressee.

In more detail, as far as the legal meanings of these acts are concerned, and according to Article 288 of the “Treaty on the Functioning of the European Union”, “a directive shall be binding, as to the result to be achieved, upon each Member-State to which it is addressed, but shall leave to the national authorities the choice of form and methods” and “a decision shall be binding in its entirety upon those to whom it is addressed.”

In the following some details taken from some of the most remarkable and recent ones are listed.

4.1.1 European Directives

The Directive 2012/34/EU of the European Parliament and of the Council of 21 November 2012 (establishing a single European Railway Area) recasts the Directives 91/440/CEE, 95/18/CE y 2001/14/CE and provides general indications about some crucial aspects. Here below some examples of such indications are listed, which are mainly related with:

- The efficiency in the railway system
  - The efficiency (energy, operation, etc.) in the railway system should be improved in order to integrate it into a competitive market.
  - To apply discounts to railway undertakings to promote the efficient use of infrastructure.

- The performance of the network
  - It’s desirable for railway undertakings and the infrastructure manager to be provided with incentives to minimise disruption and improve performance of the network.

- The investments in the infrastructure
  - Investment in railway infrastructure is necessary and infrastructure charging schemes should provide incentives for infrastructure managers to make appropriate investments economically attractive.

- The need of a Network Statement
  - All the information required to use of access right to services in service facilities should be published in a network statement.
Directive 2009/72/EU presents the main principles and ideas, which have to be incorporated into local contracts for establishing and using a railway traction current settlement system, that are obligatory for all. The principles are as follows:

- Secured transfer of data from an onboard system to a settlement system and transfer of data between different settlement systems of different countries;
- Metering system is economically reasonable and cost-effective. Thus, the railway operators should have access to their consumption data and associated prices and services costs;
- Prepayments should be close to the expected consumption of electricity;
- Different payments system must be non-discriminatory;
- Duties of infrastructure manager to society refer to security of electricity supply, regularity, quality and price. All these items in long terms are involved with the environmental protection;
- The infrastructure manager has to ensure transparent contractual terms, general information about the contracting parties, services and dispute settlement mechanisms.

4.1.2 European Decisions


Most of its contents are technical requirements, and it allows for innovative solutions. Where these are proposed, the manufacturer or the contracting entity shall state the deviation from the relevant section of the TSI. The European Rail Agency will finalize the appropriate functional and interface specifications of the solution and develop the assessment methods.

Many of the topics considered by these European Decisions are related with energy recuperation criteria.

The above Decision of 6th March 2008 indicates that AC power supply system shall be designed to permit the use of regenerative braking as a service brake, able to exchange power seamlessly either with other trains or by any other means. The substation control and protection devices in the power supply system shall allow regenerative braking.

DC power supply systems are not required to be designed to permit the use of regenerative braking as a service brake. However, where it is permissible to do so, it shall be recorded in the Infrastructure Register.

Commission Decision of 26th April 2011

The Commission Decision of 26 April 2011 concerning a technical specification for interoperability relating to the ‘energy’ subsystem of the trans-European conventional rail system [notified under document C (2011) 2740] (CR Energy TSI), states that DC power supply system shall be designed to permit the use of regenerative braking as a service brake at least by exchanging power with
other trains, and that information about possibility of the use of regenerative braking shall be provided in the Register of infrastructure.

This Commission decision also concerns a technical specification for interoperability relating to the rolling stock subsystem — ‘Locomotives and passenger rolling stock’ of the trans-European conventional rail system [notified under document C(2011) 2737] (CR LOC&PAS TSI).

About Regenerative brake (point 4.2.8.2.3) with energy to the overhead contact line, it states that electric units which return electrical energy to the overhead contact line in regenerative braking mode shall comply with the clause 12.1.1 of EN 50388. However, it shall be possible to prevent the use of the regenerative brake. In fact, point 4.2.4.4.4 (Dynamic braking command) says that if a unit is equipped with a dynamic brake system, it shall be possible for the driver to prevent the use of regenerative braking on electric units so that there is no return of energy to the overhead contact line when driving on a line which does not allow that.

**Commission Decision of 21 February 2008**


About brake system requirements (point 4.2.4.3), it considers energy recuperation when applying electric braking: where the electrical installations (the sub-stations) permit, the return of electrical energy generated in braking is permissible, but this shall not cause the voltage to exceed the limits defined in EN50163.

The above documents also contains recommendations about electric energy consumption measuring equipment, which are specified in more detail in the following paragraphs about energy meters standardization.

### 4.1.3 European Studies and Standards

There are also European studies and standards that provide technical and legal support to the development of the railway energy management. Some of the most relevant documents are discussed below.

The study Traction current settlement system – Interoperability unit (Ref.: ERA/REP/07-2011/INT v1.0 of 14.April.2011), is mainly focused on:

1. the legal and technical aspects associated with application of the Third Party Access concept (TPA) in relation to the supply of traction current to railway undertakings;
2. the possibility of specifying, within the Technical Specifications for Interoperability (TSI), the requirements for a railway traction energy settlement system;
3. the assessment of the likely scale of costs associated with implementing TPA in relation to settlement and on-board metering.

However, it does not seek to fully assess and quantify the wider impact of TPA on the railway business.

To sum up, and in relation to non-technical constrains for the consumption and management of electricity, the study analyses the compatibility of the Railway Directive (2001/14/EC) and the
Railway Interoperability Directive (2008/57/EC, including TSI’s) with the Energy Market Directive (2009/72/EC), uncovering issues such as the impact of the railway system being considered a Closed Distribution System or the options for the railway undertaking to choose an energy supplier different from the Infrastructure Manager.

The study proposes several alternatives for traction current regulation, considering the status quo, and two approaches of the Railway Undertaking, as a Third Party Access party, to the energy network, one by regulating the provision of energy under the Railway Directive and another one applying the Energy Market Directive.

Figure 47: RU and IM interface for energy measuring system and data communication.

Measuring energy on-board and data transmission from on-board to the ground collector and from a ground collector to another ground collector are also key elements discussed. These items also are related with the main topics of UIC code 930, on exchange of data for cross-border railway energy settlement (1st Ed. Sept. 2009), which contents are more described in the following paragraph about the issues on data communication for energy meters.

4.1.4 National Standards

Spain

As far as Spanish situation is concerned, the electric activity is regulated by the Electric Sector Law (54/1997 and 17/2007) that is a transposition of European Directives 2003/54/EC and 96/92/EC. This law is developed in different regulations (Royal Decrees, Ministry Orders, etc), of which some are listed below.

Royal Decree (RD) 1955/2000 of 1st December “Regulation of transmission, distribution, supply and commercialization activities in the Electric System” defines the legal frame of these activities and the relationship between them in the electric power system.

Royal Decree (RD) 661/2007 of 25th May “Regulation of electric generation activity in special regimen” stipulates the constraints in special regimen generation (cogeneration, solar, etc) and the access to the electric power grid.

RD 3275/1982 of 12th November about “Technical conditions and security in power plants, substations and transformer centres” is also applicable.
The railway activity is regulated by the Railway Sector Law (39/2003) that is a transposition of European Directives of first railway package. This law is developed in different regulations (Royal Decrees, Ministry Orders, etc.), of which some, similar to electric activity regulations, are listed below.

**Royal Decree 1434/2010 of 5 November** about interoperability in the Spanish railway network stipulates that Technical Specifications for Interoperability (TSI) must be applied in new and upgrading projects.

**Ministry Order (MO) 897/2005 of 7th April** sets out the nature of the infrastructure which is available to railway operators, conditions for access to the infrastructure and the assignment of capacity.

About local legislation on regenerative braking energy injection to the electricity grid, during the Ministries Council of 1st August 2008, it was approved an Energy Saving Plan which considers, between other, the promotion and development of the regenerative brake system of rail vehicles, as an energy saving option.

This option is developed by the Royal Decree 1011/2009 “Regulation in Change of Supplier-Office” of 19th June, which sets up the conditions for electricity consumers who implement their own energy saving systems, to inject electricity to the electricity network when necessary. This returned energy to the grid is to be discounted from the energy acquired in each access point. The Decree clearly stipulates that regenerative braking energy can flow from traction substations into the electric power grid if the manager administrator has developed an energy saving plan, and that this energy must be remunerated.

**RD 1110/2007 of 24th August** “Regulation of measured points in the Electric System” regulates the technical characteristics in measured points in order to measure the power flows and consumptions. Infrastructure manager applies this regulation in its energy meter equipments of traction substations.

Particular conditions and right for access and connection to the electricity transport and distribution network for qualified consumers are defined in the Royal Decree 1955/2000 of 1st December (Title 4, Chapter 2, Articles 60-66). Energy providers, commercial agents, transport and distribution network managers, etc., participate in the process.

**U.K.**

Referring to U.K., the standards set out by the “Energy Networks Association”, which is an independent body set up to maintain and promote safety, reliability, efficiency and sustainability within the gas & electric distribution industry, are taken as reference.

The key ENA standards are:

1. **G38/1 1985** - Operational procedure associated with electricity supplies for traction purposes on AC and DC electrified Lines.
2. **G56/1 1996** - Arrangements for Access by EA Member Company Staff to Railtrack Infrastructure.
3. **P24 1984** - AC traction supplies to British Rail.

Further non-electrical constraints may be found within Network Rail’s own internal standards, including NR/L1/ELP/27000 – Asset Management Policy for Electrical Power Assets.

The main standard for electricity metering onboard trains is a Railway Group Standard GM/RT2132 entitled “On-board Energy Metering for Billing Purposes”

The key areas discussed within ENA standards, and the specific agreements associated with them, are as follows:

1. Ownership of infrastructure.
2. Maintenance responsibilities.
3. Access requirements and processes for maintenance/renewals.
4. Permit requirements for cross-boundary working.
5. Limits of voltage/current fluctuations from both parties.
7. Electromagnetic Compatibility.

The key non-electrical aspect which may affect energy consumption on the network is the criteria and guidance relating to when to renew or replace equipment.

Sweden
Most of standards are the equivalent national of European standards:

SS-EN 50160 Voltage characteristics of electricity supplied by public distribution systems.

SS-EN 50329 Railway applications - Fixed installations - Traction transformers.

SS-EN 50341 Overhead electrical lines exceeding AC 45 kV.

SS-EN 50423 Overhead electrical lines exceeding AC 1 kV up to and including AC 45 kV.

SS-EN 61936 Power installations exceeding 1 kV ac

It should be noted that the Swedish legislation is not harmonized to Energy Directive 2009/72/EC.

4.2 CONTRACTUAL RELATIONSHIP BETWEEN ENERGY SUPPLIERS AND RAILWAYS

4.2.1 Billing payment criteria, procedures/frameworks for energy provision to railways

The features of the contracts, the kinds of billing and the way the energy is measured are at the present very fragmented through the different countries, including, but not limited to, the above listed scenarios (see introduction).

Particularly some scenarios are below analyzed in more detail.
Spanish scenario

Provision of energy in railways is regulated by ADIF Network Statement that it’s published in MO 897/2005 of 7th April. It is updated in General Secretary of Infrastructure Resolution of 3rd April 2013.

This document is a transposition of the Directives 2002/14/UE and 2012/34/EU.

In Spain, ADIF is the infrastructure manager and RENFE-Operadora is the most important railway operator.

The infrastructure manager buys the electric energy through an energy commercialization company, but it is possible also that he will buy the energy directly in the market of electricity as qualified consumer.

Railway operators cannot directly buy the electrical energy in an internal market of electricity. The traction energy is paid to the Infrastructure Manager, who is transparent in this service and transfers the real cost of energy to railway operators plus an additional cost related to:

- Maintenance of measurement equipment;
- Contract management of traction current in electric power market;
- Management inherent to service provision.

This energy bid is divided in 20 geographical lots, distinguishing some isolated electrical network such as commuter networks, high speed corridors or railway stations.

The price charged is according to the internal daily electricity market price, plus a profit fee for the service. However, it is possible to fix the price from one date to the end of the year, applying the internal future electricity market price.

There aren’t limitations if the power is higher than the nominal power during short periods of times.

There aren’t obligations to reduce the power under the nominal power during short periods of time.

In high speed rail system with services running on AC lines (1x25 and 2x25 kVac); the infrastructure manager directly transfers the real electricity costs to the railway operator, This cost is associated with real measures being referred to the traction substation consumption measures, previous discount of infra manager traction services (examination services in electrified tracks by locos and internal tests with its own rolling stock), including an additional cost of management. Currently, the operator defines the internal share of cost between its different rail services provided.

In conventional rail system, with services running mainly on DC lines (3 kVdc), the infrastructure manager firstly bills the energy consumed depending on the tonne-kilometer run by the train units by applying a management fee, in euros per gross tonne-kilometer (€/tkb), to the railway operators. This fee depends on the kind of service and train unit (commuter, regional, freight, locomotive, EMU, etc.) as identified in a list provided in the Network Statement report. And secondly, the infrastructure manager adjusts the price periodically according to the real cost associated to the energy consumption measured in the substations previous discount of auxiliary services (signaling, communication, railway switches, etc). The measure is made in traction substations and in
transformer substations, most of them have telemetry. The consumptions are recorded in packets of short periods of time and the information can be read in real-time.

To sum up, the railway operator pays the energy bill according to the cost of the real consumption measured by the infrastructure manager in its substations. In the case of new high speed lines, the national operator, RENFE Operadora is the only electricity consumer, and cost incurred by the infrastructure manager for energy supply in the associated procurement lots are transferred to the national operator. In the case of conventional lines, infrastructure manager undertakes a pre-assignment of energy cost for each kind of service, and operators adjust it depending on the final tonne-kilometer run by the specific services.

Real on-board measurements are not being taken into account at the moment, but the infrastructure manager and the main railway operator are working together in order to develop a suitable “Data Model” and to allow it in a liberalized railway market with other railway undertakings running electrical units in the railway network.

Depending on the results of this project, if a railway operator will have the intention of paying the real energy consumption of each train in railway network, the on-board energy meter system will have to fulfill this standard (under preparation) about “data model on-board for billing” which will be mandatory in the next future.

This development is leading to new requirements for energy meters on-board for billing purposes.

Presently the main operator has on board energy meters already installed in more than 50% of trains for internal use.

**UK scenario**

There are no specific procedures regarding regulation which apply specifically to the railway industry. In most respects, railways are treated equally to other large industries within the UK; however, as with other industries, they are limited by existing agreements with the electrical industry on a site-by-site basis with regard to the demand that can be taken.

For large supplies over 100kVA, including traction supplies, there are two ‘capacities’ which Network Rail (the infrastructure manager) has agreed with the distributor. These are expressed in MVA and are principally:

1. **Firm Service Capacity**
   The contracted capacity limit which defines the rate of energy which can be drawn from the incoming supply feeder. This includes for normal working, plus an ‘n-1’ condition, i.e. the failure of one adjacent supply point.

2. **Conditional Service Capacity**
   This is a discretional capacity limit which the infrastructure manager draws when an ‘n-2’ condition exists, i.e. the failure of two adjacent supply points. This is not contractually agreed with the supplier, and so should be agreed in advance if an n-2 condition is likely to exist.

Train operators cannot sign energy supply contracts directly; however they can fix their own price for electricity with the supplier using the Infrastructure Manager’s contract.

This depends also on the type of rolling stock and service.
Freight services are charged on a gross tonne-mile basis at a basic rate.

For passenger services there are three charging regimes, depending on the type of rolling stock and whether they have meters fitted or not:

1. Gross tonne-mile charging basis on a basic rate if non-metered loco-hauled stock
2. Model-based charging basis on a basic rate if non-metered multiple unit stock
3. On a metered basis if the train is fitted with metering equipment.

For unmetered services, the Infrastructure Manager implements a reconciliation process at the end of each financial year to align consumption on the network with estimated consumption. Any train metered consumption and non-train usage (i.e. signalling & stations) is deducted from the network consumption before the reconciliation takes place.

Estimated consumption is modelled based on the route of the train, including for example:

- Train Characteristics
- Stopping pattern
- Route gradients
- Known speed restrictions

The way the Infrastructure Manager pays the energy supplier is always based on meters at the substations.

**Swedish scenario**

The Nordic countries (Denmark, Finland, Norway and Sweden) have a common market for electric power (energy). The energy is traded mainly on Nord Pool Spot and the price varies during the day. Deficiency or surplus in one region or country is normally balanced by an exchange of electric power through the high-voltage transmission grid connecting the different regions and countries.

On the Nordic market a number of production modes are used, hydro power, nuclear power wind power and coal fired power plants. The different modes are used to varying extent from year to year, depending mainly on the availability of hydropower and closure of nuclear power plants, etc. This affects the generation cost of energy.

The Swedish Infrastructure manager purchases energy on the spot market Nord Pool Spot on hour-based price which also depends on the geographical position of the supply station where power is intaken into the rail power supply system. Besides this, they also purchase 20% of their estimated annual consumption 5 years ahead. This is for reducing the energy price variations over the next five years due to variations on the spot market.

At present there is no clear interest in the possibility to chose power provider, from the undertakers (operators) point of view.

The infrastructure manager Trafikverket is both a supplier and distributor of electrical power. So far this is considered not to be in conflict.

Train operators cannot sign energy supply contracts directly.
Energy intaken at the supply station from the public grid is measured. Besides total energy for traction and vehicle heating via heating posts, associated losses in supply station and catenary and vehicles are also included in the metering and charged for indirectly. The losses are charged for all tractive units according to a template based on experience. In addition, taxes and “power transmission fees” are added on the price.

Auxiliary power is measured by other energy meters.

The final price for tractive power paid by the undertaker, operator, is determined in two ways depending on whether energy metering is present or not on the vehicle.

If energy metering is not present aboard the tractive unit, the total power consumption with losses is preliminary estimated according to a ‘template’. The total gross weight of a train is multiplied by running distance and three factors. The first factor represents power consumption based on experience for that particular type of tractive unit and train type and service. The second factor, $E=1.16$, represents a basic average loss factor. Factor three takes into account associated reactive average losses that depend on type of traction equipment and its efficiency.

Since the power consumption estimated with the template method is only preliminary and differs from the true measured consumption, the difference in measured and estimated consumption is distributed among all tractive units not equipped with energy meters at the end of the year.

If energy metering is present, then only the cost for the measured consumed energy is paid multiplied by the factors taking into account estimated associated losses plus taxes and fees.

The bill is paid according to real measures and the total power is measured by the provider and Infrastructure manager, with energy meters installed at intakes from the public grid.

### 4.2.2 Kind/level of standardization for the energy meters

Considering that the way to energy consumptions and costs minimizations can imply an increased attention for the operators to real consumptions, the issues connected with an agreement and standardization of energy meters are of great importance.

Most of the countries have undertaken activities aimed to energy meters standardization/certification.

Most of reference standards are local/national, however it should be noted that implementation of the set of EN50463 standards about “Railway applications- Energy measurement on board trains” (December 2012) should be considered in the next future.

Within Spain network the energy meters equipment in traction substation must fulfill RD 1110/2007 of 24th August. These equipments must be certified. Each certification has an expiration date.

In the U.K. the energy meters at the substation are the property of the Infrastructure Manager but are managed by an approved metering company. It is a requirement under Schedule 7 of the Electricity Act 1989 that all meters (i.e. primary and secondary) used for billing purposes must be of an approved pattern or construction and installed in an approved manner. The pattern or construction of the meter type must conform to the requirements specified in the accompanying Regulations:
The Meters (Approval of Pattern or Construction and Manner of Installation) Regulations 1998, SI 1565;


In Sweden the reference standards for energy meters are the following:

- BVS 1543.14242
- BVS 543.14110
- BVS 543.14120
- IEC 62053-22 Electricity metering equipment (a.c.) – Particular requirements – Part 22: Static meters for active energy (classes 0.2 S and 0.5 S)
- IEC 62053-23 Electricity metering equipment (a.c.) – Particular requirements – Part 23: Static meters for reactive energy (classes 2 and 3)
- IEC 62056-21 Electricity metering – Data exchange for meter reading, tariff and load control – Part 21: Direct local data exchange
- SS-EN 50160 Voltage characteristics of electricity supplied by public distribution systems, subharmonics

4.2.3 Main present issues/problems related with standardization/calibration of energy meters and data communication

The above standardization is surely to be related with the need of providing technical specifications aimed to meet the essential requirements and ensure the interoperability of the trans-European rail system (as described in Directive 2008/57/EC), and in line with the technical specifications for interoperability (TSI).

This implies a number of issues, mainly related with situations where on-board energy meters are used and mounted on trains running transnational routes, especially about calibration and data communication.

The set of EN50463 standards about “Railway applications- Energy measurement on board trains” (December 2012), already mentioned at previous paragraph, includes technical requirements for energy meters and data handling and communication, and defines conformity assessment criteria. Many of these issues are also described within Annex “D” of “Commission Decision of 26 April 2011 concerning a technical specification for interoperability relating to the rolling stock subsystem - Locomotives and passenger rolling stock’ of the trans-European conventional rail system”.

Different parts of above standards refer also to the issues arising from the needs of a trans-European rail systems.

Standardization/calibration of energy meters

The “Commission Decision of 26 April 2011 (concerning a technical specification for interoperability relating to the rolling stock subsystem - Locomotives and passenger rolling stock’ of the trans-European conventional rail system”), in relation to energy metering (point 4.2.8.2.8. Energy consumption measuring function) applies to electric units and states that if an electric energy consumption measuring equipment is installed, this equipment can be used for billing purposes and the data provided by it shall be accepted for billing in all Member States. The technical requirements for the equipment are identified in Annex D of the same document.
The fitment of an energy measuring system shall be recorded in the rolling stock register defined in clause 4.8 of the same TSI.

Commission Decision of 21 February 2008 concerning a technical specification for interoperability relating to the ‘rolling stock’ sub-system of the trans-European high-speed rail system (at point 4.2.8.3.5 Energy consumption measuring devices) indicates that if energy consumption measuring devices are to be installed on board trains, one device shall be used which shall be able to function in all Member States.

Standard EN50463 part 1 – General, at point 4.2.4.1 states that an EMS shall cover all traction supply systems types that the traction unit can operate on. If an EMS is used for more than one traction supply system, it shall continue to function correctly when changing between systems, and log each change of traction supply system. The EMS shall measure energy consumption within 1 s. of the change to the new traction supply system.

Although above indications define the correct path in order to achieve a proper and approved use of on board energy meters in different countries, it should be noted they are still general statements needing a further step forward in order to agree on a wide basis standardized components which can be recognizable and identifiable for billing purposes.

This problem still remains an open point, which is to be directly associated with calibration issues and the need of sharing an agreed calibration criterion.

Provided that technical requirements of European standard will have to be fulfilled by all energy meters, items such as features of current/voltage sensors and energy measurement functions, and accuracy classes will have to be analyzed and shared in more detail in order to have a common approach.

Moreover, it should also be noted that the difficulties related with this problem are enhanced by the situations, present in most of the countries, where energy meters have only recently been installed, or are currently being installed, and where present standards implementation is still on-going. In fact on board energy meters calibration is any way a complicated matter, and more difficult than calibration on fixed installations.

For example in Sweden, no energy meters have yet been calibrated on traction units, despite some of them have been in use since 2005. One reason for this is related with difficulties in coordination between the energy meter calibration and the maintenance of the traction unit and between calibration and life length of batteries and of energy measurement unit. Also considering that such lifetime (including that of the equipment around the energy meter) is around 7-10 years, old energy meters are planned to be replaced by new energy meters and no calibration of on-board meters is presently foreseen.

Considering the above analysis, it is to be pointed out that listed standards/commission decisions provide a basis for further developments, and a guide line indicating a standardization/integration target, which can be really achieved by following below detailed steps through the different member states:

- Analyze and solve practical problems about calibration
- Analyze situation/state of the art about European standards implementation
• Ensure/ascertain technical characteristics/certifications/conformity assessments for energy meters
• Monitor situation about national on-going projects on energy meters installation/standardization (for example for the Spanish situation)
• Perform a common ground analysis on calibration situation/criteria
• Involve widely all member states, including those having a more consolidated experience on on-board energy meters (i.e. Germany and Austria, in which basically the Operator is billed on the real consumptions measured by “accepted” meters installed on board)

All the above steps would be necessary in order to achieve an agreed/approved calibration criterion, and it is suggested they are to be encouraged by a common/wide involvement of the member states led by the competent European organizations and institutions.

Data communication
Another issue is related with data communication.

The on-board measuring system shall include a Data Handling System merging data from the Energy Measurement Function with time data and geographical position, producing and storing the complete series of data with true energy values (in kWh/kVarh) ready to be sent by a communication system.

The DHS shall use, as a time reference, the same source of clock as in the EMF, and shall incorporate data storage with a suitable memory capacity, having a capability to be interrogated locally by authorised personnel on board the train.

The compiled data suitable for energy billing shall be stored ready to be transferred in chronological order and shall contain the information specified at item 2.2.6 of Commission Decision of 26 April 2011.

On the basis of these requirements, the importance of a harmonized and homogeneous approach and methodology is evident.

Moreover, in relation to communication data requirements, an open point of the Loc&Pas TSI relates to the communication from on-board Energy Measuring System (EMS) to on-ground Data Collecting Service (DCS). This is to be found within the “final draft merged Loc&Pas TSI 13 dec. 2012” and is currently under discussion within European Railway Agency, given the need of ensuring that each DCS will be able to collect data from all on-board EMS.

In relation to this, it is expected for 2014 a new standard to be published dealing with general considerations on communication from on-board to ground (EN 61375). Thus also EN 50463 could be updated to define an exact communication protocol.

Presently, UIC code 930 proposes an exchange protocol to exchange data between on-ground servers, and it could be relevant reference for development of on-board to on-ground communications.

In more detail, the leaflet proposes a business model to exchange energy metered data collected by train units in different railway networks for proper energy billing during international services.
The business model relays on the Railway Interoperability Directive and on technical standards. It also develops processes for the measured data transfer communications based on a methodology recognized by the European energy sector.

4.2.4 Energy flow back from the railways network to the external power network

Spanish scenario

In relation to reversible substations the infrastructure manager, in collaboration with the operator, is fixing AC substations to cope with electric market needs, in order to officially recognize energy injection to the public grid. Particularly in 1x25 kV and 2x25 kV ac systems, traction substations are flowing regenerative braking energy to the electrical power grid (high speed line Madrid-Valencia) where this injected energy, in five of these substations, is being recognized and compensated to the infrastructure manager (who is the agent in contact with energy transport and distribution companies to manage the energy supply to the railway system) by the electric utilities, since February 2013 (it’s discounted from the acquired energy in each access point). Most of this cost saving is transferred to the operator. Infrastructure manager, in coordination with the main operator, is planning to modify all these substations in order to get the same remuneration, and the experience is being extended to other high speed lines in Spain, being the next one the Madrid-Barcelona line. Currently, economic energy net savings in the line Madrid-Valencia is reaching 8% of the energy cost expended in such a line.
In 3 kV d.c. system, infrastructure manager has transformed a dc traction substation from non-reversible to reversible (in the commuter line Málaga-Fuengirola). The reversible part is going to be put into service during the next months. The energy that flow from the substation to the electrical power grid will be remunerated by the electric utilities. The reversible section is made with a dc/ac inverter that uses IGBT technology. The inverter is anti-parallel connected respect the existent rectifier. The nominal power of inverter is less than the existent rectifier.

However, investment cost is relevant in these cases, and requires a previous viability study. Particularly, in this case, after analysis of the line and rail services, just the central substation has been upgraded to allow electricity injection to the public grid. Now, final measurement of energy savings is being undertaken to fix the optimal final setting of the substation. A final report is foreseen for the middle of July 2013.

Moreover, the reversible section is not running permanently, it only runs under some technical requirements (level of voltage in overhead contact line upper than a certain value, etc).

As discussed above, recognition of the injection to the electricity grid is coming true since February 2013 for High Speed AC lines, and is under development for Conventional DC lines.

**UK scenario**

All AC network grid supply points can record both the amount of electricity supplied to Infrastructure manager, and the amount returned to the electricity network. Where the connection is with National Grid, the export is netted from the import. For Distribution company connections, the electricity is ‘sold’ at ~94% of the rate it was purchased at.

**Swedish scenario**

Energy fed back to the public grid is not measured (only consumed energy is measured). No compensation is given back to infrastructure manager for AC 50 Hz or AC16 2/3 Hz system.

This is also due to the fact that having a subscription where Trafikverket is paid for this energy fed back would cost more than any payment for the energy itself. However, it should be noted that almost all regenerated energy is used by other trains and that the amount of any fed back energy to the public grid is generally very small.

It is also to be highlighted that at the end of 2013 Trafikverkets new energy measurement criteria will be taken into use and then all energy fed back to the public grid will be measured.

**4.2.5 Possible technologies for energy storage/regeneration (used or planned to be introduced)**

In Spanish case, the infrastructure managers are developing a pilot project to investigate the convenience of placing energy storage devices in key points along the railway network. Particularly, an experience is being carried out in Atocha station (main station in Madrid), where it is possible the local generation in special regimen RD 661/2007 of 25th May for internal consumption (natural gas cogeneration).

It is also being studied to install electric generation with renewable energies (solar) in some specific railway stations. An experimental flywheel (2x 350 kW) in a 3 kV dc substation has been installed but nowadays this technology is considered expensive.
In UK situation, they have regenerative braking operating on the majority of 25 kV ac rolling stock and on approximately half of the 750V dc rolling stock. There are no current plans to install energy storage technology onto infrastructure or the operators’ trains.

In Sweden, the tendency is that loco hauled trains with no possibilities to regenerate are successively being replaced by EMUs resulting in relatively more regenerated power.
APPENDIX

1. RAILENERGY’S KPIS

1.1 INTRODUCTION

The assessment of the energy consumption was standardized within the Railenergy project by usage of the Key Performance Indicators KPIs for Railways.

The KPIs are as follows:

- KPI 1 – Final energy consumption per traction effort
- KPI 2 – Final energy consumption per offered transport
- KPI 3 – Primary energy consumption per actual traffic output (facultative)
- KPI 4 – Final energy consumption per actual traffic output
- KPI 5 – Share of energy consumption for parked trains
- KPI 6 – Energy recuperation rate
- KPI 7 – Efficiency of the railway distribution grid.

1.2 KPI 1 - FINAL ENERGY CONSUMPTION PER TRACTION EFFORT

The following table shows the unit of KPI 1.

<table>
<thead>
<tr>
<th>KPI 1</th>
<th>Final Energy consumption per traction effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>$\frac{kWh}{t \cdot km}$</td>
</tr>
</tbody>
</table>

Table 12: KPI 1

The definition of equation elements are:

\[ E_N \] … Final net energy consumption measured at the point of common coupling, defined as inflow minus outflow from the entire railway system

\[ T_{eff} \] … Traction effort being total train mass multiplied by the total train kilometers simulated

The Key Performance Indicator KPI 1 is:

\[ KPI_1 = \frac{E_N}{T_{eff}} \]
1.3 KPI 2 – FINAL ENERGY CONSUMPTION PER OFFERED TRANSPORT

The following table shows the Unit of KPI 2.

<table>
<thead>
<tr>
<th>KPI 2</th>
<th>Final Energy consumption per offered transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>$\frac{kWh}{seat \cdot km}$</td>
</tr>
</tbody>
</table>

Table 13: KPI 2

The definition of equation elements are:

$E_N$ ... Final net energy consumption measured at the point of common coupling, defined as inflow minus outflow from the entire railway system

$O_T$ ... Offered transport being number of seats multiplied by the total train kilometers simulated

The Key Performance Indicator KPI 2 is:

$$KPI_2 = \frac{E_N}{O_T}.$$ 

1.4 KPI 3 – PRIMARY ENERGY CONSUMPTION PER ACTUAL TRAFFIC OUTPUT (FACULTATIVE)

This KPI was not calculated within the Railenergy project.

1.5 KPI 4 – FINAL ENERGY CONSUMPTION PER ACTUAL TRAFFIC OUTPUT

The following table shows the Unit of KPI 4.

<table>
<thead>
<tr>
<th>KPI 4</th>
<th>Final Energy consumption per actual traffic output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>$\frac{kWh}{passenger \cdot km}$</td>
</tr>
</tbody>
</table>

Table 14: KPI 4

The definition of equation elements are:

$E_N$ ... Final net energy consumption measured at the point of common coupling, defined as inflow minus outflow from the entire railway system

$T$ ... Actual traffic output being the number of passengers multiply by the total train kilometers simulated
The Key Performance Indicator KPI 4 is:

\[ KPI_4 = \frac{E_r}{T}. \]

### 1.6 KPI 5 – SHARE OF ENERGY CONSUMPTION FOR PARKED TRAINS

The following table shows the Unit of KPI 5.

<table>
<thead>
<tr>
<th>KPI 5</th>
<th>Share of energy consumption for parked trains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>%</td>
</tr>
</tbody>
</table>

**Table 15: KPI 5**

The definition of equation elements are:

\[ E_p \] … Energy consumption of trains in parked mode (measured at the pantograph)

\[ E_N \] … Final net energy consumption measured at the point of common coupling, defined as inflow minus outflow from the entire railway system

The Key Performance Indicator KPI 5 is:

\[ KPI_5 = \frac{E_p}{E_N}. \]

### 1.7 KPI 6 – ENERGY RECUPERATION RATE

The following table shows the Unit of KPI 6.

<table>
<thead>
<tr>
<th>KPI 6</th>
<th>Energy recuperation rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>%</td>
</tr>
</tbody>
</table>

**Table 16: KPI 6**

The definition of equation elements are:

\[ E_R \] … Recuperated energy of trains measured at the pantograph

\[ E_G \] … Final gross energy consumption measured at the point of common coupling, defined as inflow into the entire railway system

The Key Performance Indicator KPI 6 is:
\[ KPI_6 = \frac{E_R}{E_G} \]

### 1.8 KPI 7 – Efficiency of the Railway Distribution Grid

The following table shows the Unit of KPI 7.

<table>
<thead>
<tr>
<th>KPI 7</th>
<th>Efficiency of the railway distribution grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>%</td>
</tr>
</tbody>
</table>

Table 17: KPI 7

The definition of equation elements are:

- \( E_N \) … Final net energy consumption measured at the point of common coupling, defined as inflow minus outflow from the entire railway system
- \( E_{Pa} \) … Net energy of trains in operation mode measured at the pantograph.

The Key Performance Indicator KPI 7 is:

\[ KPI_7 = 1 - \frac{E_N - E_{Pa}}{E_N} \]

### 1.9 Different Applications of KPIs

The following summary shows the main applications of Railenergy’s KPIs:

- UIC statistics – total and average of many companies, either per service types or aggregated averages
- Company annual totals typically including “empty runs”, to and from workshops, etc. (also estimations)
- Direct measurements for specific lines: out of service (e.g. tests for homologation) or in-service (“from station A to B”)
- Simulations using the Railenergy global modelling methodology

### 2. Railenergy’s Verification, Evaluation and Assessment Process

#### 2.1 Introduction of Railenergy’s Methodology

For an integrated approach the analysis is subdivided into strategic, operational and technical levels. The project structure and workflow is depicted in Figure 49 and described in the following.
On the strategic level, the complete railway system consisting of different subsystems is analyzed with respect to energy, CO2 savings and costs, followed by a technical and economical evaluation.

The operational level uses the results for the simulation of the complete railway systems in the so-called “Global Model”. It is based on a common structure for the input and output data, enabling the simulation of the three typical Demonstration Scenes (DS) for high-speed, long-distance and regional traffic as well as freight traffic. In this part energy-efficient operation with respect to driving mode, timetabling and dispatching is also taken into account.

The technical level provides standardized models for the simulation tools and develops analyses and specifies innovative energy-efficient technologies. It is subdivided into traction power supply, rolling stock traction systems and components and topologies. The overall results of the simulations and strategic measures are evaluated by means of the KPIs and finally assessed, also taking into account economical aspects.

### Figure 49: Overview methodology

#### 2.2 VERIFICATION, EVALUATION AND ASSESSMENT PROCESS

The steps of the assessment process can be summarized chronological as follows:

- Development of New Technologies in Technical Level
- Definition of KPI in Strategic Level
- Definition Demo Scenes and Use Cases in Operational Level
• Definition of simulation assumptions and boundaries for all simulation teams in order to ensure the comparability of results in Operational Level
• Plausibility checks of simulations in Operational Level
• Calculation of KPI for Base Case and New Technologies in Operational Level
• “Operational Evaluation” of New Technologies per Demo Scenes including experts estimations & verification with help of external sources in Operational Level
  ▪ Evaluation Reports
• “Economic Evaluation” of Demo Scene per New Technology in Operational Level
  ▪ Technology Potential Tables
• Final assessment with respect to RailEnergy’s Goals in Strategic Level
  ▪ Strategic Assessment Report

2.3 LESSONS LEARNED AND FINDINGS FROM SIMULATION, VERIFICATION, EVALUATION AND ASSESSMENT PROCESS

The following lessons learned can be summarized. They had been collected during a brainstorming session within the in RailEnergy involved engineer team of Siemens AG IC SG RE.

• The different commercial multi train simulation tools produce comparable and mostly consistent outputs.
• A range of commonly agreed assumptions have influenced the achieved simulation results.
• As expected simulation KPI values are lower than real measured values due to the tendency of worst case assumptions for simulations.
• Simulation of different driving styles is difficult to align with realistic situations due to the lack of complexity.
• KPI’s for parked trains and regeneration are very sensitive to selection of number of train sets, peak/off peak settings, etc.
• The “Plug & Play” principle for simulation model of virtual new components has proven to be not feasible.
• Evaluation and assessment process turned out to be too complex.
3. RAILENERGY’S ENERGY EFFICIENT TECHNOLOGIES

3.1 OVERVIEW

Within the RailEnergy project the following technologies were developed: Energy Efficient Train Operation (EETROP)

- Reversible DC substation
- Real time management
- 2 x 1.5 kV dc traction system
- Asymmetrical Autotransformer system
- Parallel substation
- Increased line voltage
- Reduced line impedance
- Trackside energy storage
- Onboard energy storage
- Waste heat usage by using absorption refrigeration
- Superconducting Traction Transformer System
- Medium frequency traction power supply
- Hybrid diesel electric propulsion with permanent magnet synchronous machines
- Reduction of vehicle coasting loss
- Active filtering technology to reduce input passive filter losses
- Reuse of converter energy loss

The following chapters describe the technologies mentioned above in detail.

3.2 ENERGY EFFICIENT TRAIN OPERATION (EETROP)

3.2.1 Technology description

The concept of Energy Efficient Train Operation comprises the saving of energy and other resources through better planning and handling of train operations. Introducing energy efficiency and power management into timetabling as well as real-time operations enables timetable planners, dispatchers and drivers to manage their traffic in the most efficient manner whilst fully respecting the underlying mandatory conditions such as punctuality, capacity, etc.

The phases and proposed tools are:

- EETROP Planner – Timetabling
- EETROP Manager – Power and tariff management
- EETROP Dispatcher – Real-time planning of traffic
- EETROP Driver – Onboard driving advice
3.2.2 Advantages of the new technology

The main advantage is that maximum efficiency is achieved via energy saving as the most efficient timetable can be planned as well as real-time supervision, overall traffic planning and driving control of individual trains. Previous existing technology only looked at individual trains and had very little scope for handling deviations from the planned schedule.

3.3 Reverseable DC Substation

3.3.1 Technology description

Reversible DC substations enable the recovery of almost all regenerative braking energy (99% of recoverable regenerative braking energy) into the upstream network, having given priority to natural exchange between trains. This is carried out by combining a controlled rectifier/inverter with a software control function to be able to recover braking energy between nominal voltage (Un) and maximal voltage (UMax2) according to EN 50163. Advantages compared to existing technologies: the new technology offers maximum efficiency compared to parallel inverter or storage systems (flywheel and super capacitors) combined with a diode rectifier, enabling the removal of braking resistors on board of traction units without transferring additional load to mechanical braking.

3.3.2 Advantages of the new technology

The main advantage of this new technology is that maximum energy-efficiency can be achieved as braking resistors are not used on traction units. The recovered energy is available all along the line for commuter trains or at stop points when the distances between passenger stations are greater. The capacity for energy recovery using this new technology can be very large compared to storage systems.

3.4 Real Time Management

3.4.1 Technology description

Real Time Management, transposed into Energy Efficient Train Operation (EETROP), includes the monitoring of power feed in all substations, working with the power provider to compile a daily reference diagram featuring power needs, forecasting power requirements based on on-line timetables, optimizing global energy demand and smoothing out the power demand curve, forwarding recommendations to Automatic Train Supervision (ATS) for economical driving.

3.4.2 Advantages of the new technology

As Real Time Management is an entirely new concept, it is difficult to compare with existing technologies. Currently rail traffic is monitored on a daily basis with the objective of providing on time freight and passenger services. Economic driving technologies are available and enable energy efficiency on individual trains. Additionally, a rail energy management system optimizes a complete train schedule, taking global power constraints into consideration.
3.5 2 x 1.5 kV DC TRACTION SYSTEM

3.5.1 Technology description
The idea of the 2x1500V is to use existing or new feeders and to set their capacity at a different level to that of the catenary. These feeders are supplied with power by new converters installed in existing substations.

3.5.2 Advantages of the new technology
Owing to the 2x1.5 kVdc system, the main expected results can be seen below:

- Reduction in the number of new substations required
- Increase the distance between consecutive substations
- Reduction in the energy required from the grid
- Reduction in DC losses
- Saving catenary reinforcements
- Making the most of existing feeders
- Improving 1.5 kV dc rolling-stock feeding system performance
- Reduction in DC stray currents

3.6 ASYMMETRICAL AUTOTRANSFORMER SYSTEM

3.6.1 Technology description
This new technology includes an increase in the rated voltage of the negative feeder in 25kV 50Hz AT systems. Initially the overhead line and track are not changed except for the negative feeder which is moved laterally in order to meet insulation requirements. The effect of the voltage increase is to reduce loop impedance, reduce line currents, increase pantograph voltage for a given train performance, and consequently reduce transmission losses. No attention is paid to distribution of currents with respect to low frequency magnetic fields. The same concepts can also be employed in 15 kV systems.

3.6.2 Advantages of the new technology
The application of the Asymmetrical Autotransformer System causes a reduction of the losses in the Railway Transmission network. Very low energy losses occur due to the fact that the baseline autotransformer technology is already very efficient for modern AC Railways. Furthermore a slight increase in voltage at the pantograph can be observed.

3.7 PARALLEL SUBSTATION

3.7.1 Technology description
The approach of the new technology “parallel substation for AC 25 kV railway power supply systems” balances load flow control in three-phase distribution, which may be able to deal with the challenges arising from connecting substations in parallel to a three-phase high-voltage transmission grid.
Usually AC 15 kV 16.7 Hz railways systems have a double-sided power feed, thus permitting larger feeding distances and fewer substations. This option has been discussed for many years, also for 50 Hz power supplies, where until now single-sided feeding prevails. However, in recent years various technologies for balancing load flow control in three-phase distribution systems have been developed, which may be able to deal with the challenges arising from connecting substations in parallel to a three-phase high-voltage transmission grid. The parallel substation technology for 25 kV 50 Hz systems can be used for two different purposes: energy saving application (by using conventional distances between substations of AC 25 kV and 2AC 25 kV 50 Hz systems) and reduction of investment costs (by lengthening distances between substations (for new tracks)).

### 3.7.2 Advantages of the new technology

In case of the energy saving application the transmission losses along the line can be reduced and slightly increased regeneration is expected for AC 25 kV 50 Hz and 2AC 50/25 KV 50 Hz. In case of reduction of investment costs AC 25kV 50 Hz and 2AC 50/25 KV 50 Hz can be configured with considerably enlarged feeding sections, hence requiring less investment in substations and connections to the three-phase high-voltage grid.

### 3.8 INCREASED LINE VOLTAGE

#### 3.8.1 Technology description

The DC 4 kV system can be regarded as an upgraded DC 3 kV system. By using higher nominal voltages both transmission efficiency and regeneration can be improved considerably. The DC 4 kV system demonstrates considerably improved energy efficiency and permits increased substation spacing. For higher supply voltages (e.g. 4 kV) the substation equipment and the electronic devices of the trains have to be adapted to this voltage level. Whether changes would be necessary in current 3 kV systems is dependent on the level of insulation on the existing overhead line equipment. Considerable investment in research and modifying existing installations could therefore be necessary. On the other hand, taking into account ongoing developments in semiconductor technology, this might become an attractive option for high-power systems, though not in the immediate future.

#### 3.8.2 Advantages of the new technology

- Increased system performance due to higher train voltage
- Possible increase in substation spacing
- Reduction in line losses
- Higher regeneration rates

### 3.9 REDUCED LINE IMPEDANCE

#### 3.9.1 Technology description

The approach of the new technology “reduced line impedance” consists of the reduction of losses along the line of electrified railway systems. The losses are caused by the impedance or resistance of the contact line system and the current which is supplied to the locomotive vehicles. The
reduction in impedance or resistance is achieved through higher conductivity of the materials of the contact line systems and/or by enlarged cross sections of contact line systems.

For AC-systems a reduced line impedance is achieved by using better quality magnesium alloyed copper conductors (RiM) or other advanced copper alloys for high use systems. The manufactures of contact wire produce RiM conductors with improved electric conductivity and less manufacturing tolerances, these features are guaranteed for the material. Hence the effective contact line resistance, causing the thermal losses of the catenary, is reduced. Where reinforcing feeders are used, the appropriate cross sections and conductivity should be optimised, especially with regard to losses. In case of DC-systems the increasing of the effective copper cross section of DC-lines in order to achieve reduced line losses by means of lower resistance and reduced voltage drop.

### 3.9.2 Advantages of the new technology

Increased electric conductivity of catenary conductors leads to a reduction in transmission losses in the contact line system. This technology is ‘the simple approach’. The losses in the traction power supply for AC systems, when compared to the energy demand of the whole system (point of common coupling), fall in the range of 5-10 %. Investment in infrastructure is only partly recommended because of low potential energy savings for AC systems. Application of contact line material with higher conductivity is advised in the course of regular contact line replacement. The losses in traction power supply for DC systems, when compared to the energy demand of the whole system (point of common coupling), fall in the range of 10 % to 35 %. Investment in infrastructure is recommended because of high potential energy savings for DC systems. The application is implemented by increased cross sections of contact wires, messenger wires and/or additional feeder wires.

### 3.10 Trackside Energy Storage

#### 3.10.1 Technology description

Introduction of trackside energy storage units to absorb energy generated by braking vehicles and store it until it can be fed back into the power supply system by the storage unit when vehicles are accelerating. The storage system operates in parallel with the existing traction power supply system and is based on double-layer capacitor technology. Trackside energy storage can be used in two different operation modes: In case of the energy saving application the trackside energy storage absorbs energy generated by braking vehicles and stores it until it can be fed back into the power supply system by the storage unit when vehicles are accelerating. For voltage stabilization the trackside energy storage operates as a voltage stabilizer. Energy levels are kept high and energy is released when system voltage falls below a specified limit.

#### 3.10.2 Advantages of the new technology

- Improved utilization of regeneration.
- Peak power limitation
- Increased system performance in terms of train supply voltage
- Technology can be used without changing the existing system, just by adding new components at certain locations, in contrast to the competing inverter technology which
requires permission for connection to the power supply and most likely modifications in the connection.

3.11 ONBOARD ENERGY STORAGE

3.11.1 Technology description
Onboard energy storage systems represent enormous potential for energy saving in traction applications. Diesel Multiple Units are probably the most suited vehicle type where energy storage and reuse of brake energy can recover the normally wasted brake energy and lead to energy savings of up to 30 or 40%. This saving can be measured directly in terms of reduced fossil fuel consumption per 100km. In addition there will be emission savings of the same order or even higher since the small diesel engine can be operated in an optimal fashion. The optimal size and operation mode of such a storage system depends on the application under consideration and operational conditions. An ideal option could be a diesel power pack comprising a diesel engine and a generator based on the asynchronous or synchronous principle, with an active or passive rectifier delivering the DC-Link power which is fed through the inverter to the traction motors supplying wheel power. During braking the wheel power is transferred to the DC-Link through the inverter and either stored or dissipated via heat in the brake resistor. Both components are connected to the DC-Link via a controlled chopper allowing the power distribution between both components to be changed.

3.11.2 Advantages of the new technology
Onboard energy storage enables the traction equipment to store braking energy which can be reused during acceleration.

There are two main saving aspects when considering onboard energy storage:

- Time saving, which corresponds to the capability of supplying additional power to the DC-Link in booster operation.
- Energy saving, which corresponds to the capability to operate the diesel engine in an energy optimized range or shorter operations when using the booster operation and coasting with the engine running idle.

3.12 WASTE HEAT USAGE BY USING ABSORPTION REFRIGERATION

3.12.1 Technology description
This technology enables the re-use of waste heat from a Diesel Multiple Unit (DMU) for heating and cooling. The study was made for DMUs only. EMUs were not taken into consideration. The use of the waste heat from the diesel engine cooling circuit is state of the art. The re-use of the waste heat leads to a reduction in demand for auxiliary power and, furthermore, cuts fuel consumption. In the foreseeable future new solutions will be available to implement absorption refrigeration machines in mobile applications. The waste heat is provided by the exhaust air from the diesel engine.
3.12.2 Advantages of the new technology
A significant reduction in fuel consumption can be achieved using exhaust air from the diesel engine, the energy from which would normally be lost, for heating and for cooling.

3.13 Superconducting Traction Transformer System

3.13.1 Technology description
The MVA Superconducting Traction Transformer System (STTS) including Transformers, Reactors and Closed-Cycle Cryogenic Cooling System can be used in energy efficient traction systems for high-speed passenger trains. The windings are made from High-Temperature-Superconducting wire and cooled by pressurized liquid nitrogen. The transformer can be applied in multi-systems trains for international operations in countries using AC 16.7 Hz/15 kV and AC 50 Hz/25 kV. These advantages will be most notable in future high-speed passenger trains.

3.13.2 Advantages of the new technology
In comparison to conventional traction transformers (operating at line frequency with copper conductors), an STTS such as this promises the following benefits:

- Lower energy consumption, even when the necessary cooling supply is included.
- Reduced volume and weight.
- Oil-free operation of transformer and cooling system (environmental benefits, reduced fire hazard).

3.14 Medium Frequency Traction Power Supply

3.14.1 Technology description
Medium Frequency Traction Power Supply is a converter which is connected via a line choke to the high line voltage. With this solution, implementation of a line frequency transformer at the power supply’s front end can be avoided. It consists of a cascade of 4 quadrant converters, each equipped with an individual DC-link. A high DC-link voltage requires only a low number of sub-converters in cascade. To adapt the DC-links’ electric potential to the common DC-links feeding the motor inverters, medium frequency (MF) DC/DC converters with MF-transformers, which excel at low mass and volume, are used. Hereby savings can be made in both overall mass and energy consumption. The innovative component is the medium frequency and high voltage DC/DC converter that links the primary and secondary DC-links.

3.14.2 Advantages of the new technology
- Increased efficiency.
- Decreased mass savings regarding vehicle construction (axle load limit).
- More flexible installation, e.g. distributed installation.
- Range of application.
3.15 HYBRID DIESEL ELECTRIC PROPULSION WITH PERMANENT MAGNET SYNCHRONOUS MACHINES

3.15.1 Technology description
Permanent magnet synchronous motors (PMSM) can be used as traction motors. PMSMs are lighter, more compact and efficient than other electric machines. The energy supply of PMSMs traction motors is a diesel engine with a PMSM generator. The generator supplies energy alternatively to a diode and to an insulated gate bipolar transistor rectifier. Both types of rectifier were examined. From the DC-link of the inverter, auxiliary drives and passenger comfort systems can be supplied easily with power. The integration of an optional DC-link into the energy storage system was also investigated.

3.15.2 Advantages of the new technology
The advantages of this technology are:

- Efficient operation of the diesel engine
- Efficient power supply for passenger comfort systems
- Easy integration of an energy storage system, which enables the reuse of braking energy and the possibility to downsize the diesel engine at equal traction power.
- More compact and lighter electric motors are used for the generator and the traction motors.

3.16 REDUCTION OF VEHICLE COASTING LOSS

3.16.1 Technology description
Energy consumption of a rail vehicle is closely related to the operating conditions of the main components during normal service. Inverter and motor losses can represent significant power consumption, as can be seen when the effective power consumed during coasting is examined. Coasting losses increase with speed. The purpose of this technology is to eliminate traction inverter and induction motor losses due to magnetizing current during coasting. To achieve this power saving, new driving styles combined with switching off the power supply to the inverter have been investigated.

3.16.2 Advantages of the new technology
During coasting, the inverter could be turned off or the motor flux could be managed to reduce losses. The use of a dedicated algorithm to estimate the motor flux during turn-off will be used in order to achieve a rapid turn-on transient.

3.17 ACTIVE FILTERING TECHNOLOGY TO REDUCE INPUT PASSIVE FILTER LOSSES

3.17.1 Technology description
The use of active filter algorithms for harmonic reductions was developed specifically for low frequencies, such as 75Hz, in the Netherlands. The dimensions of the input filter inductor can be
reduced and consequently, weight saving can be achieved. The traction inverter is used to compensate for low frequency harmonics. The fundamental idea is to measure the 75Hz harmonic from the DC-link voltage and to use this signal to perform a proper action:

- on the modulation index of the inverter in PWM (Pulse Width Modulation) mode;
- on the fundamental frequency in Full Wave mode.

3.17.2 Advantages of the new technology
The active filtering achieves a reduction in size and weight in filter inductance.

3.18 Optimised Management of Medium Voltage Loads for Energy Saving - Optimisation of the Auxiliary and Cooling Systems

3.18.1 Technology description
The proposed technology concerns optimized MV (Medium Voltage) load management for cooling systems. When maximum cooling performance is not requested, for example at low speed or during the train stops, fans and pumps can operate at reduced speed or be turned off to reduce energy consumption and environmental impact.

3.18.2 Advantages of the new technology
The benefits of this technology are:

- Energy saving
- Reduced environmental impact like reduction in noise, blowing up dust, ventilation channel clogging snowy conditions

3.19 Reuse of Converter Energy Loss – Reuse of Waste Energy for the Reduction of Auxiliary Consumption

3.19.1 Technology description
Energy produced through the operation of power and auxiliary converters, braking rheostat, main transformer and inductors is dispersed into the surrounding environment using cooling fluids: air, water and oil. The goal of this research was to recover part of this waste energy to reuse it in the vehicle. On top of the air outlet channel, a diathermic oil heat exchanger has been installed. The heat from the waste hot air is transferred to the finned tubes and then to the oil. A hydraulic system circulates and controls the diathermic oil to enable heat recovery.

3.19.2 Advantages of the new technology
Lower power absorption of auxiliary converters can be achieved by reusing the recovered energy for heating or cooling.