Efficient recovery of braking energy through a reversible dc substation

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Abstract

The full regeneration of the braking energy is one of the most promising sources of energy savings to transport system operators.

This paper presents the outcome of a RailEnergy cooperative research program focusing on reduction of energy consumption in transport systems.

Today, urban transportation systems are generally fed at 750 Vdc or 1,500Vdc via rectifier bridges and trains are equipped with modern 3-phase ac traction packages. This allow for easier and more effective implementation of dynamic braking over a wider range of speed and voltage with the possibility of feeding back some of the energy via the 3rd rail or OCS to adjacent trains.

The target of this project is to improve the line receptivity of dc power systems by transferring the excess energy to the ac side and thus regenerate it, via the transformer, to the ac medium voltage distribution network that is naturally receptive. This concept transforms the traditional unidirectional dc traction into a reversible one. It is suitable to all known types of dc traction power supply systems from 600Vdc up to 3,000Vdc.

The key benefits expected from reversible dc traction substations are:

- Regeneration of 99% of the braking energy at all time, while maintaining priority to natural exchange of energy between trains; this will allow eliminating the braking resistors, and thus reduce the train mass and heat release;
- Regulation of its output voltage in traction and regeneration modes to reduce losses, and increase the pick-up of energy from distant trains, and
- Reducing the level of harmonics and improvement of the power factor on the ac side.

Under an Alstom funded internal R&D programme two 750 Vdc prototypes dc reversible substations were built and tested on a dedicated tramway test-track at the Alstom plant in La Rochelle France.

To reduce development time & costs the prototypes were built using state-of-the-art industrial variable speed drive converters, active harmonic filters, high power semiconductors modules, modern controls and protections, modularity, high integration while taking into account the specific requirements of the railway industry.

The test results confirmed the theoretical findings and demonstrated that the reversible substations allowed regenerating all of the excess available kinetic energy of the tramway.

Keywords: reversible; substation; regeneration, energy savings.

INTRODUCTION

The 1997 UITP operator survey on metropolitan railways energy consumption [1] established that some of the networks operating trains fitted with modern traction package enjoyed significant energy savings, up to 40% of the energy absorbed by the trains during the traction phase, through regeneration. In these rare cases the high line receptivity is essentially associated to the high train density and their high auxiliary consumptions. However, most dc fed networks generally do not operate in such favourable conditions and excess braking energy cannot be regenerated back to the internal or external users and is generally dissipated into on-board braking resistors. This is an intrinsic feature of dc fed systems as they use diode rectifiers that only allow unidirectional flow of power, making it impossible to regenerate the excess braking energy outside of the dc network.

Throughout the years various attempts to reuse that excess braking energy were investigated through wayside or on-board solutions energy storage systems. Use of inverters was also investigated to regenerate that excess energy to the ac networks. None of these solutions associated with a diode rectifier substation yielded attractive internal rate of returns (IRR) and never flooded the market.

The increasing focus on energy savings and the reduction of the carbon footprint led to the creation of RailEnergy [2], a UNIFE [3] R&D initiative funded by the European Commission. The following section gives a brief presentation of the RailEnergy mandate, its working groups and the associated R&D programmes and finally the results and recommendations to be made to the UNIFE.
THE RAILENERGY R&D PROGRAMME

As indicated on its website, RailEnergy is an Integrated Project co-funded by the European Commission under the 6th Framework Programme for Research and Development to reduce the energy consumption of railways. It is a four-year project and was initiated in September 2006. The concluding conference of the project took place last November 2010 in Brussels.

The main objective of the project is to address energy efficiency of the integrated railway system and to investigate and validate solutions ranging from the introduction of innovative traction technologies, components and layouts to the development of rolling stock, operation and infrastructure management strategies.

The overall project structure is presented in Appendix 1, Table 1 for information.

The work presented in this paper was part of the SP3 Energy (NRG) Trackside workgroup led by RFI (Italian Rail Network operator). The following section details the roles and responsibilities of the SP3 subgroups.

THE RAILENERGY PANEL 3 R&D PROGRAM: INNOVATIVE ENERGY EFFICIENT TRACKSIDE

The 3 working sub-groups (see Table 1 in Appendix 1 covered the following activities:

- SP 3.1: Headed by NITEL, modelled the power distribution system
- SP 3.2: Headed by Alstom looked at improving existing ac and dc power supply architecture. Four types of power supply were investigated:
  1. Reversible dc substation (Alstom)
  2. Real time energy management (Alstom)
  3. 2x1.5 kV dc system (SNCF)
  4. 2x25 kV asymmetrical ac system (Siemens)
- SP 3.3: Headed by Siemens looked at the definition of new dc and ac power supply architectures.

The simulation and evaluation of the most promising technologies were done following the process defined under SP2 (please refer to Appendix 1, table 1 and summarised in Figure 1 hereafter).

This paper reports on the activities of the SP3 NRG trackside workgroup and on the Harmonic and Energy Saving Optimiser (HESOP) an Alstom internal R&D project designed to validate the theoretical findings on a test track.
SCOPE & OBJECTIVES OF THE REVERSIBLE DC SUBSTATION R&D PROGRAMME

The scope of the programme included the assessment of potential solutions, the selection of the most promising one, the preparation of the associated design specifications and the preparation of the associated testing and validation plan, the fabrication of the prototype and its test on a dedicated test track.

The objectives of the programme were to validate the following:

- Regenerate over 99% of the retrievable braking energy,
- Confirm the feasibility of removing on-board braking resistors,
- Demonstrate the feasibility of dynamic power balancing between adjacent substations to
- Demonstrate the ability to compensate dynamically fluctuations of the primary voltage, control overloads, and avoid penalties on power contract subscription,
- Demonstrate the ability to achieve the total harmonic distortion (THD) as defined by the relevant standard,
- Demonstrate the ability to compensate the reactive power as per the local provider requirements,

METHODOLOGY

The programme was implemented per the following methodology:

- Identify the potential for energy recovery for suburban and regional lines operating at line voltages of 1.5 kV and 3 kV,
- Design and build a power converter meeting the traction and braking efficiency targets in the defined operating domains
- Design and build a reversible substation using the power converter identified above providing for active filtering, reactive power compensation, load balancing between adjacent stations
- Validate the potential energy savings via simulations and testing
- Evaluate the LCC and the IRR of the proposed solution.

POTENTIAL FOR ENERGY RECOVERY ON SUBURBAN AND REGIONAL LINES

For this study, applied to railway systems, suburban and regional lines were defined as lines with inter-station distances of 1.5 km and 4 km respectively under 1.5 kVdc and 3.0 kVdc. It also includes two theoretical high-speed lines with inter stations of 10 km and 30 km powered at 3 kV.

The potential for energy regeneration is essentially based on the number of trains on the line, characterised by the headway, the installed power on each train and the speed of the trains when applying brakes, the frequency of braking and the auxiliary consumption. Power simulations using multi-train simulator running on typical operation as described above were run and plotted the traction power, the net braking power (excluding energy exchanged between trains) per km of line as a function of headway.

Figure 2 hereafter presents the result of these simulations.

Figure 2: Linear net Braking Power (absolute)
The simulation results indicate that for headway of 5 minutes or less inter-vehicle exchange was prevalent and most efficient. For headway greater than 5 minutes, regenerating back to the ac side become more efficient. This study also establishes that there is a potential for energy savings for suburban and regional railway systems. While no simulations are shown here for urban systems application, similar type of curve were obtained.

CONVERTER MODEL
The underlying requirements of the converter were defined through specific development tasks the end result of which was to establish the performance and definition of the prototype converter.

Three areas were explored:

- The rectifier and its operating domain in traction mode
- The structure of the inverter and its efficiency,
- The operating domain of the inverter in braking mode.

RECTIFIER DESIGN AND OPERATING DOMAIN (TRACTION MODE)
The standard 750 Vdc diode bridge rectifier operating domain is defined by the diode characteristic in the (I, V) domain. Its characteristic is a constant negative slope between the no load voltage (around 800V) and the 3In voltage where at In is the current through the diode at 750V. This operating domain affects the ability to regenerate, taking into account fluctuations of primary voltage as well as the legacy maximum bus-bar voltage of 900 Vdc. This translates into a maximum regeneration range of 70 V. To palliate this issue, the standard diode rectifier was replaced by a thyristor controlled one. This allows adjusting the rectifier input voltage independently of the load around the nominal voltage. Thus it increases the regeneration domain range from 70V to about 150 V.

The resulting operating domain of the rectifier bridge is presented in Figure 3 hereafter.

INVERTER EFFICIENCY TARGET
One of the goals of the RailEnergy program was to improve the overall efficiency of converters to maximise the energy savings.

Figure 4 hereafter summarises the efficiency targets that were given to the designers of the inverter.

INVERTER OPERATING DOMAIN (BRAKING MODE)
As indicated earlier, the thyristor-controlled rectifier bridge allows maintaining substation output voltage at the nominal value, which increases the ability to regenerate. As the line receptivity drops, the regeneration voltage increases. But if no loads are within the range of the regenerating train, this energy will be wasted. To increase the regeneration range allowing higher voltage is necessary.

The increase of the maximum voltage was introduced through a standard change in 2004. For all dc system, EN 50163:2004, has introduced a higher voltage in regeneration mode. For 750 Vdc, the maximum allowable is now 1,000 Vdc, thus allowing a 250V voltage drop to pick up regenerative energy from distant trains. Regenerating at higher voltage is also beneficial from a line losses point of view.

Figure 5 presents the operating domain of the inverter of the reversible substation.
The Converter also increases the power traction power capability maintaining a high current level all the way to the lowest voltage allowed. Finally the proposed converter will have several functions, all related to the program objectives, i.e., active filtering of the harmonics generated by the controlled rectifier bridge and by the load, power factor improvement and power load management.

REVERSIBLE SUBSTATION ARCHITECTURE

Figure 6 presents the architecture of the selected power converter model. It is based on off the shelf industrial devices selected to meet the requirements of the project at the lowest cost possible.

It consists of a thyristor rectifier bridge associated with an IGBT converter with the function described in the previous section and the associated dynamic voltage controller. The rectifier bridge operates in the traction mode only. While in traction mode, the inverter operates as an active filter. In braking mode it regenerates the energy back to the ac side. Both rectifier and inverter are controlled dynamically with a single controller that switches from one mode to the other without any dead time. Structure and component specifications for a power converter prototype were prepared to conduct the prototype validation phase.

DESIGN VALIDATION - SIMULATIONS

The design was validated within RailEnergy through simulations using the electrical model of the reversible substation. It was evaluated in accordance with pre-defined demonstration scenarios with involving EMUs operating on a real regional service from Utrech to Zwolle totalizing 87 km of track and 15 passenger stations and 16x1500V DC substations of unit power from 6 to 18 MW.

The evaluation was carried out by an independant consultant (ENOTRAC) and used a multi-train simulation tool to compute the energy efficiency. It also computed as Key Performance indicators compared to those of a base line scenario fitted with standard diode rectifier substations.

For the purpose of simulation, the characteristics of voltage versus current and losses versus current in rectifier and inverter modes for reversible substation were given.

This work is now achieved and compared to the basic scenario the results of energy saving on normal daily operation scheme is –7%, which is estimated quite good for a regional service with an average distance between passenger stations of 6.2 kilometers.
DESIGN VALIDATION – TEST

Based on the results of the simulations, ALSTOM decided to proceed at its own expenses, with the construction of a prototype substation power converter with the aim to further test and validate this new technology with vehicle(s) on a test track. This project is named HESOP™ for Harmonic and Energy Saving OPtimizer.

To cope with the RailEnergy validation program, a low-power prototype (750 Vdc /300 kW) of the converter was selected. Two units using different technologies were manufactured.

The converters were provided by CONVERTTEAM, a former subsidiary of ALSTOM, a specialist in industrial speed drive converters.

Figure 7 on the right presents the converter being assembled.

The two prototype reversible substations were installed on the La Rochelle test track, adjacent to Alstom La Rochelle plant where trams Citadis Trams are manufactured.

Figure 8 below presents the site characteristics and the location of the prototype reversible substations.

TEST SITE SET-UP

The test site power architecture is shown in Figure 9 hereafter.

Shelter 3.2 contains the water-cooled converter module and is fed via the existing substation transformer. Shelter 3.1 is a self-contained air-cooled substation as it includes the transformer as well.

The different possibilities of feeding the line and testing are:

- Feeding by one substation either by the diode rectifier or controlled rectifier,
- Feeding by two substations either two controlled rectifier or mixed including diode rectifier,
- Regenerating to the upstream network by one or two inverters.

A bidirectional counter of energy was installed by the electricity provider in the connection to the national grid.
TEST RESULTS – REGENERATION OF BRAKING ENERGY

Synchronised Digital recorders were installed into the substations and the tramways.
Figure 10 hereafter presents the simulation results related to the regeneration of braking energy where:

- $U_{\text{in,sh3.2}}[\text{V}]$ is the voltage across the inverter in shelter 3.2
- $U_{\text{sh3.2}}[\text{V}]$ is the voltage at the output rectifier in shelter 3.2
- $U_{\text{Tram,LR}}[\text{V}]$ is the voltage at the tram pantograph
- $I_{\text{Tram,LR}}[\text{A}]$ is the tram current draw
- Recuperation entre = Regeneration between

The set up was such that the tram was the further away from Shelter 3.2 to achieve a full traction-braking cycle and get a full assessment of the amount of energy regenerated with the minimum voltage.
The test indicate that the all the dynamic braking energy was regenerated back to the grid with a minimum voltage of 765 V at the inverter input.
The target voltage in braking of 750V was achieved in subsequent tests with higher current draw.

TEST RESULTS – PRIORITY TO EXCHANGE OF ENERGY BETWEEN VEHICLES

Figure 11 presents the results associated to this test.
The definitions are similar to those of the preceding graph with the addition of a second tram (red trace for current draw)
The right part of this diagram shows:

- one tram in traction mode and the other one in braking mode, supplying the first vehicle
- the sequence of the two substations in inverter mode recovering the surplus of current and shifting in rectifier mode according to load sharing without dead time whilst the traction current draw is increasing
REAL CASE ANALYSIS
Alstom is now committed to introduce this technology to Clients.
In a recent tramway tender with the following characteristics:
- 750V Power supply
- Line 14 km, with 27 stations
- Operational headway: 5 to 15 minutes
The simulations yielded the following results:
- Line receptivity: >99%
- Annual energy saving: -18% of basic scenario at the HV connection point

ADDITIONAL VALIDATION TESTS
During most of 2009 Alstom conducted extensive tests on the reversible DC substation to validate:
- Energy saving targets and energy balances from long operation periods,
- Power quality delivery and energy recovery,
- Environment: Noise, Electromagnetic compatibility,
- Compatibility with adjacent diode rectifier,
- Load sharing between adjacent substations,
All tests were satisfactory, confirming the initial confidence in this new technology. Alstom is now ready to guarantee the performance of the HESOP reversible substation on a case-by-case basis.

NEXT STEPS
Following the successful demonstration test of the concept, a Requirement Specification for 1500 and 3000 V reversible DC substation and a project of a TecRec (Technical Recommendation as initiated by UIC/UNIFE) was proposed before the end of the project (Nov 2010). This will enable the evolution of the railways standards according to the progress of the technologies.
In addition, Alstom is finalizing an industrial plan to develop and manufacture (600), 750, 1500, 3000Vdc reversible substations ranging from 600 kW to 8 MW for mass transit and railway applications. These ongoing R&D efforts extend the range of energy-saving solutions deployed by the Alstom in its quest of providing sustainable development for railways.

ACKNOWLEDGEMENT
HESOP is internal R&D project that was conducted in partnership with Converteam within the framework of the RailEnergy EU with the support of ADEME [R4]: in France.

REFERENCES
[R1]: UITP 52nd International Congress STUTTGART 1997: Reducing Energy Consumption in Underground Systems
[R2]: RailEnergy: EU Sixth Framework Program; http://RailEnergy.org/
[R3]: UNIFE - Association of European Railway Industry
[R4]: ADEME – STEEM Project
Table 1: RailEnergy Project Structure

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