Publishable Summary for 22NRM04 e-TRENY
Metrology support for enhanced energy efficiency in DC transportation systems

Overview

DC railway and metro systems, that are supplied by unidirectional substations, demonstrate a significant waste of energy due to their inability to fully recover the energy produced by electric braking. Bidirectional substations and/or storage systems are expected to significantly improve energy efficiency, but current equipment and procedures lack a determination of the actual overall efficiency performance as well as the efficiency of components e.g. power transformers and converters. In order to address these issues and the needs expressed by IEC TC9, CENELEC SC9XC and CENELEC TC14, this project will develop new methodologies for DC transport efficiency determination, that combine accurate on-site measurements with circuit models of the railway electric system.

Need

The transport sector, in particular road vehicles, is responsible for almost one quarter of Europe's greenhouse gas emissions. The modal shift to public transport with electric rail as a backbone (urban rail in urban areas) is a priority, and the EU policy to support the development of sustainable and smart mobility will lead to a consequent increase of energy consumption by electric rail transport. However, a major weakness in the efficiency of DC transportation systems is the limited recovery of the electric energy generated during the electrical braking of the trains. Estimates show that up to 1 GWh per year, about the annual consumption of 365 families, can be wasted in one single commuter line.

This situation can be significantly improved by the introduction of bidirectional power converters and storage systems that allow the injection of the braking energy into the upstream AC grid or in the local storage system. However, before this can be rolled out widely, electric transport operators, supply designers and developers need standardised methodologies and procedures that support substation procurement and allow accurate and reliable evaluation of the actual efficiency of power transformers and converters and system energy saving under real operating conditions. This is needed in order to verify the compliance with the designed efficiency and to quantify the cost/benefit ratio in a more realistic way.

CENELEC/TR 50646 has declared standardisation needs for the traceable determination of efficiency for different operation modes (traction, regeneration) and the determination of the performance of harmonic compensation on AC and DC side. With the increased efficiency of modern power converters and power transformers, CENELEC TC14 has also called for on-site determination of their losses under actual operating conditions, which requires accurate and traceable measurements. In addition, accurate loss determination under real operating conditions requires new and improved traceability that includes distorted and dynamic conditions.

Objectives

The overall objective of the project is to support enhanced energy efficiency in DC railway systems, via new traceable methods for on-site measurement of the efficiency of substation transformers and converters and for

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measurement of the efficiency increase achieved by the adoption of energy recovery systems such as non-conventional bidirectional substations or energy storage systems in commercial service.

The specific objectives are:

1. To provide an overview on possible configurations for non-conventional DC substations (e.g. bidirectional and/or with storage systems) including evaluation of pros and cons. To perform a survey of real installations focusing on the design characteristics and the expected or declared energy savings. To establish a suitable measurement approach and to design instrumentation for on-site measurement campaigns.
2. To develop a metrological infrastructure for calibration of high voltage (3 kV) and high current (1000 A) DC transducers and measurement systems under dynamic conditions with typical timescales from a few hundreds of milliseconds to a few seconds.
3. To develop, calibrate and apply on-site setups and algorithms for the measurement of the energy losses of non-conventional AC/DC substations and the charge-discharge efficiency of electric storage systems with an overall on-site target uncertainty of 10 % of losses. The setups allow capturing signals from DC to 20 kHz to perform Power Quality and transient event analysis.
4. To develop, characterise and determine the accuracy of a hybrid method based on the combination of field measurements and models for the determination of the energy saving provided by the upgraded DC supply system in real operating conditions.
5. To contribute to standards development of technical committees CENELEC TC9X, CENELEC TC14 and IEC TC9 aligning project outputs to their needs, with rapid communication including to final users (e.g. DC transportation system operators, manufacturers, designers).

Progress beyond the state of the art and results

Measurement systems for on-site converter efficiency

The standards in-force on power converters for DC railway supply currently only deal with AC/DC diode-rectifier systems. Such standards state that “If the purchaser requires measurement of the losses this shall be mentioned in the procurement specification. The current admissible tolerance for losses is +10 % of the guaranteed value”. However, the standards give very little information about the accuracy of the measurement chain for losses; for example, only detailed information is provided only for 50/60 Hz power component measurements. For losses lower than 3 % (efficiency > 97 %) the standard proposes a calorimetric approach which is time-consuming and cannot be implemented on-site. This project will go beyond this state of the art by in-situ accurate and traceable efficiency determination.

This project will develop a new traceable measurement infrastructure able to measure on-site the losses of conversion systems (power transformers, power converters, storage systems) during commercial service in two test cases, (i) on the metro and (ii) tramway line. Losses of AC/DC, DC/AC DC/DC and power transformers will also be determined with an overall uncertainty better than 10 % of losses. This uncertainty is intended to allow reliable loss determination even for losses value lower than 3 %. The system will also enable the correlation of the efficiency and signal distortion up to 20 kHz.

Traceability for power measurement under dynamic and low-frequency conditions

Present calibration measurement capabilities (CMCs) for AC power declared by NMIs only deal with static, pure sinusoidal waveforms in the frequency range from 40 Hz to 100 kHz for voltage and a current amplitude of hundreds of volts and tens of amperes. No CMCs for DC power are currently declared in the BIPM database (KCDB).

In order to guarantee accurate on-site losses and efficiency measurements, this project will develop new and improved traceability for DC dynamic signals (voltage and current ramps) with slew rates from 500 A/s to 10 kA/s and from 100 V/s to 10 kV/s with amplitudes up to 1200 A and voltage 3 kV. The overall target uncertainty will be 0.01 %. Moreover, the project will upgrade the systems developed in the previous EMPIR project 16ENG04 MyRailS by providing traceable systems for AC and DC distorted power measurement even under dynamic conditions, up to 20 kV 300 A AC and 4 kV 3600 A DC. These systems will emulate the relevant load fluctuation experienced in the transportation systems.

System efficiency determination

System efficiency is currently demonstrated by manufacturers using simulations only, and without a standardised approach for the validation of the simulator in terms of reliability and accuracy. Even the standard EN 50641, released in 2020, lacks full coverage of measurement of all quantities necessary for a complete determination of system energy efficiency.

This project will develop and test a hybrid tool combining a power-flow model of the transportation system with distributed measurements performed both at substations and on-board trains. The hybrid tool will provide the energy saving introduced by non-conventional substations together with an associated uncertainty and a sensitivity estimate, as well as an estimate of how well correlated the voltage control at substations is compared to on-board trains. Information on the optimum number and position of measuring points will also be provided with the associated uncertainty.

Outcomes and impact

The project will positively influence the assessment of the energy efficiency of DC railway systems, in particular those with new bi-directional substations. Thus, providing much needed knowledge to power transformer and converter manufacturers, substation designers and installation engineers. The new instrumentation developed in the project will also allow for the first time unique on-site determination of energy efficiency (at the MW level) of power transformers and of AC/DC and DC/DC high-power converters under real operating conditions. Furthermore, the project will provide a methodology for accurate determination of energy saving introduced by non-conventional substations.

Outcomes for industrial and other user communities

The new facilities for on-site AC and DC power measurement will allow the first-ever determination of losses of high-power high-efficiency (> 97 %) converters under actual grid conditions and for dynamic load conditions. This will provide unique insight to the DC transport industry regarding the actual efficiency of railway supply systems in the presence of grid harmonics and other disturbances. Furthermore, a reliable and traceable measurement system for the determination of harmonics/ripple on AC and DC supply systems will support the verification of the electric pollution introduced by the power converters for the different operating conditions. The experience gathered by the on-site measurements (within the project) will be used to create a Best Practice Guide that can be used to simplify (and thus reduce cost thereof) on-site compliance assessment activities to the technical requirements of railway transportation systems tenders.

The project will also develop and make available a hybrid method, combining measurements together with power-flow models. This hybrid model will allow end users to determine the energy saving provided by the installation of non-conventional substation(s) in DC railway systems.

A clear and accepted definition of parameters which quantify the efficiency improvement is of vital for the trade exchange between the manufacturer (or contractor) and infrastructure owner (or operator). An example is line receptivity, a parameter that is more and more present in tender technical requirements. The project will provide a clear definition and methodology to estimate receptivity in different operating conditions using the project's hybrid model. This will prevent disputes between customers and providers of new DC railway supply systems.

Metrological and methodological tools will be produced by the project for definition of and measurement of the conditions for the optimised coordination of the reversible substation and storage system. This will support the compensation of deviations from the ideal power exchange among running trains in braking and traction conditions and will allow the removal of the dissipative rheostatic braking system from on-board trains. Ultimately, this should provide major savings to operators of DC railway systems.

To facilitate the uptake of project's outputs there will be stakeholder engagement with industrial stakeholders including railway, metro, tramway infrastructure managers, railway operators, power converter manufacturers, installation engineers, railway supply system designers. The participation of industrial participants in the project and the establishment of a Stakeholder Committee will help to ensure that the project outcomes are carefully aligned with industrial needs.

Outcomes for the metrology and scientific communities

The project’s laboratory facilities and procedures developed for the characterisation of DC and AC broadband voltage/current sensors and power measurement systems used for on-site measurements will be the basis for the submission of new CMCs under actual grid conditions (i.e., with ripple and harmonics).

The new metrology knowledge gained by the project, in the development of the new laboratory facilities and in its subsequent use for calibration and verification of the voltage/current sensors and the power measurement systems will be an important metrology outcome. This knowledge will be shared with the metrology community via communication and dissemination to the EURAMET Technical Committee for Electricity and Magnetism (TC-EM) and in particular Sub Committee (SC) Power and Energy, the EMN on Smart Electricity Grids. It is expected that the new facilities for calibration of DC voltage and current sensors in the presence of ripple, as well as the new Energy Efficiency Measurement Systems (EEMSs) for on-site efficiency measurements in transport systems will raise significant interest in the metrology community.

The project’s measurement campaigns will also provide unique data on DC railway systems, with accurate uncertainty characterisation, that will be very useful for further research into the statistical analysis of power flows, as well as for designers, who will, for the first time, have access to data that represents the real energy state of the system with information on its variability. The methodology can also be applied to different contexts (such as DC grids and micro-grids, power converter design) and used to develop designs more tailored to them.

Furthermore, the measurement campaigns will provide unique insight into the efficiency of power transformers and converters under actual grid conditions and varying load conditions. At present, there is hardly any scientific literature on this subject due to the complexity of the required measurements. This project will provide pioneering research in the loss mechanisms of transformers and converters under non-ideal conditions.

Outcomes for relevant standards

The project’s outcomes will contribute to the research priority declared by the IEC TC9 and CENELEC TC9X on the efficiency determination of power converters installed in railway DC substations and on the accurate determination of the energy saving introduced by non-conventional substations. In particular, input will be provided to IEC TC9 WG50 and CENELEC subcommittee 9XC WG11 on the measurement system and on the procedures for losses and harmonic/ripple determination.

The project addresses the need expressed by CENELEC TC14 for research on accurate on-site determination of power transformer and power converter losses under actual distorted conditions. The results of the on-site campaigns in the project and the developed methodology will be promoted within CENELEC TC14 and IEC TC11, to enable possible uptake of project results in a new technical specification.

Further to this, the project will provide input to IEC TC9 ad-Hoc group (ahG)26, IEC TC9 ahG19, IEC TC9 Project team (PT)641, IEC TC9 Maintenance Team (MT)62888 and CENELEC/IEC TC38.

Longer-term economic, social and environmental impacts

The project’s new measurement infrastructure for the traceable quantification of efficiency will provided much need information on substations under actual operating conditions and will in the long-term foster the dissemination of new energy-efficient technologies for power conversion in DC railway systems. A reliable methodology to quantify the cost-benefit ratio of new investment devoted to energy saving will also positively contribute to decision-making processes on the uptake of these investments. The increase of the braking energy recovered by the system should also have a positive contribution to the longer-term European policy for a smart and sustainable European transport system as well as benefitting climate and environment policies by helping to support CO_2 savings.

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1. INRIM, Italy
2. FFII, Spain
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4. VSL, Netherlands
5. VTT, Finland</td><td colspan="2">External Beneficiaries:
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7. SUN, Italy
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