Metrology Infrastructure for Energy and Power Quality in DC Railway Systems

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I. Introduction

The European community for over a decade is supporting scientific and technological studies in order to make public transport low environmental impact. The metrological community plays a key role in fostering this improvement, in fact all the activities described in this thesis work are carried out in the framework of the European project 16ENG04 MYRAILS (Metrology for Smart Energy Management in Electric Railway Systems). Within the project, a metrological infrastructure for accurate measurement of energy exchange and for reliable system monitoring is developed, which underpins the implementation of an energy efficient management of the European DC railway and metro system. Moreover, the supply grid of the railway system is not ideal; it is strongly characterized by a non-stationary regime and many Power Quality (PQ) events verified during the normal operations. In order to evaluate the metrological reliability of an energy meter under actual operating conditions, calibration set ups and procedures which go beyond the well-known procedures developed for pure DC regimes are required.

The topics reported in this thesis work are the following:

- introduction on railway and metro systems and general notions on dynamic braking;
- description of the realized measurement setup and transducer calibration involved in measurement campaigns;
- description of the two measurement campaigns on board the train addressed during the PhD program;
- analysis of energy flows on board a train operating in a traditional 3 kV DC railway system;
- analysis of energy flows on board a train operating in a metro system supplied with a reversible substation;
- presentation of two methodologies for the correction of errors in the measurement of dissipated energy on braking resistors;
- classification and analysis of PQ phenomena characteristic of the railway system with a focus on electric arcs;
- development, characterization and application of a facility for the laboratory and on-board calibration of energy-meter.

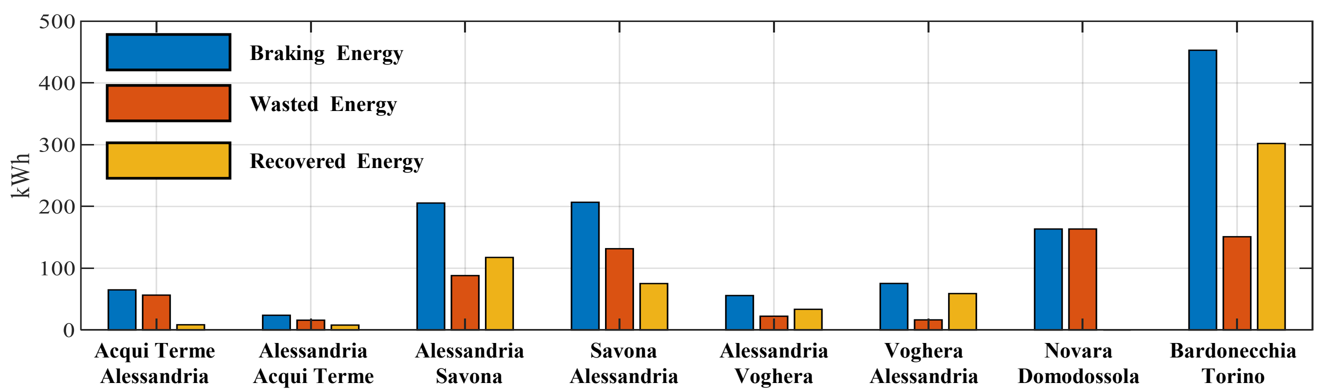
II. Measurement Campaigns

Part of this work consists in developing the measurement setups analyzing the results of two on-board DC train measurement campaigns devoted to the accurate estimate of the energy exchanged between the locomotive and the DC feeder and the electrical energy wasted during the braking stage.

The braking stage is crucial in this scenario because it allows for energy recovery thanks to the electric engines of the trains; the issue in this configuration is due to the unidirectional energy flow admitted by the AC/DC converters that supply the railway grid. Therefore, all the energy recovered by the trains during the braking stage must be absorbed by other trains or loads present on the DC side or wasted on braking rheostats.

Fig.1 provides the electric braking energy analysis of several journeys monitored in the Italian measurement campaign. Moreover, one of the two measurement campaigns is conducted onboard of a train operating on the metro line in Madrid, where a reversible substation is installed. The

Fig. 1. Braking energy analysis of several journeys in Italian 3 kV measurement campaign



reversible substation is a technical solution that allows the bidirectional energy flow between the AC and DC supply grid. In this case, the aim is to quantify the impact of these technologies in a real application, providing information on energy saving in the different operating conditions and presenting a methodology to quantify them. The impact of reversible substation was analysed by performing statistical analysis of a large number of braking events over a long-time interval taking into account separately different supply conditions (reversible substation on and off) and high and low circulating trains number. Although the reversible substation is in experimental stage and the amount of energy sent back to the main grid is limited by the law in force, the results of this comparison show that the reversible substation adoption has potential to considerably improve the overall efficiency, in particular when the number of trains is low (see Table I).

TABLE I
ANALYSIS OF THE DISSIPATED ENERGY.

Traffic conditions	**All**	**Train n.$\geq$ 9**	**Train n.$\leq$ 3**
Average E_D [kWh] Conventional	202	183	427
Average E_D [kWh] Reversible	159	145	296
Relative increment [%]	21.4	20.9	30.7

III. BRAKING RHEOSTATS

The energy wasted measure is not necessary for the billing of the dissipated energy but having an accurate and reliable knowledge of this quantity is a precious tool for collecting internal data useful in the design of more efficient DC power supply systems and real-time efficiency management of energy flows. In this context, two methodologies for the determination of power dissipated on braking resistors have been developed:

- the first is based on an offline algorithm which involves the measurement of the current, acquired with a high sampling frequency, and the compensation of the current transducer frequency response;
- the second relies on the information already available to the train control unit only. Despite its simplicity, it allows taking into account the current transient due to the presence of the rheostat inductance but it allows obtaining fairly accurate results. Still maintaining the cost low, it allows for reaching the accuracy comparable with the first methodology used as reference method.

IV. POWER QUALITY IN DC SYSTEMS

The research activity presented in this thesis work, enlarge the typology of Power Quality events found in the several TB of data provided by the measurement campaigns, with a particular focus on arc events occurring between the pantograph and overhead catenary. The measurement procedures of some of the main power quality index, well defined and widely used for conventional power systems (interruption, voltage dip/swell and harmonics) are analyzed and extended with minimal changes to become compatible with all railway systems. Proposed techniques are applied to a large measurement campaign. The obtained results were discussed, showing how the PQ indexes can be useful for predictive maintenance or to identify specific problems of the supply system and the train. Particular attention is paid to the phenomenon of the electric arc in order to provide new data to understand the dynamics of the arc discharge, how it evolves and and how it quenches when the current reaches zero ampere. In particular, the dissipated power terms associated to the arc itself and to the electric phenomena (oscillation of the onboard filter) and events (activation of the dissipative braking chopper) have been evaluated, showing that the peak power levels are notable. Thanks to this activity, the author and Domenico Giordano from INRIM have published a patent developing an algorithm for the automatic detection of the electric arcs based on the conducted effects of the latter on voltage and current signals. The exploitation of the patent, in collaboration with industrial partners, is currently underway.

V. CALIBRATION SYSTEM FOR ENERGY METER

The European commission requires that the billing for the energy consumption of the railway systems shall be computed on the actual energy consumed by 2019. Calibration setups and techniques that go beyond the well-known ones created for pure DC regimes are needed in order to assess the metrological reliability of an energy meter in real-world operational conditions. Therefore, the realization of an accurate and reliable calibration system for evaluating the measurement of the energy absorbed/exchanged between the train and the railway grids is needed. The Phantom Power Calibrator, presented in Fig.2, takes into consideration the harsh on board measurement circumstances and the frequent non-stationary electrical conditions. The uncertainty estimation is provided for different configurations (integration-time, current amplitude). In steady state tests, a worst case uncertainty of 250 μW/W has been obtained while the uncertainty contributions in dynamic tests is in worst case of 1200 μW/W. The same setup can be used as a facility to characterize the on board detection system. This because it allows to emulate signal as voltage dip and swell, electric arcs, bad-contact between pantograph and catenary and other PQ phenomena.

Fig. 2. Connection diagram of the Phantom Power Calibrator