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Fictive power source for calibrations in railway systems

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Abstract. The work presented in this paper aims at developing a reference system for laboratory calibration of the Energy Measurement Functions working under AC supply system and actual operating conditions. More precisely, the paper focuses on the design of a fictive power source designed to generate voltage and current waveforms of 15 kV-16.7 Hz and 25 kV-50 Hz, 500 A with harmonics up to 5 kHz.

1 Introduction

In order to establish a single European railway area, in 2014, the European Commission regulated the measurement and billing of electricity through two technical specifications for interoperability: that relating to the energy subsystem and the other on the rolling stock. In 2019, Member States must have set up a data collection system for billing based on the energy metering.

Today, the metrological characterization of on-board measurement equipment is based on the EN50463 series of standards [1, 2]. These standards distinguish the sensors implemented in the trains through their functions: Voltage Measurement Function (VMF), Current Measurement Function (CMF). Most trains are currently equipped with mixed sensors incorporating voltage and current measurement functions.

For the metrologist, the proximity of these measurement functions within the same equipment both in high voltage and high current requires to take into account the individual mutual influence of the two functions. In particular, it is hazardous to qualify the mixed sensor by considering these functions as independent.

The chosen solution is to develop a fictive power source capable of approaching the real operating conditions of the sensor associated with the Energy Measurement Function (EMF). The voltages supplied to trains are often distorted harmonically and subject to ripple, the currents drawn by trains also contain high levels of harmonics, inter-harmonics, ripple, and step changes in magnitude associated with train acceleration and braking [3, 4, 5]. These distortions are much higher than those experienced on the usual energy meters. The influence of these effects and their combination on the real-time power consumption and energy metering needs to be studied.

The EN50463-2 standard requires, as for domestic energy meters, a periodic verification. However, strong constraints on this energy measurement function (the material is highly solicited because it is embedded hardware) and practical constraints require that the metrological equipment can be moved to the train.

One idea to improve the metrological reliability of the energy measuring systems consists in developing a suitable generation system for calibration purposes. In the framework of MyRailS European project, DC and AC supply systems are designed to generate distorted current and voltage waveforms [6, 7]. The DC setup is planned to run at 3 kV, 1.5 kV and 600 V, 400 – 600 A, class 0.1 with ripple/harmonics up to 5 kHz.

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The reference system for calibration of EMF working under AC railway supply systems is designed for 15 kV – 16.7 Hz; 25 kV – 50 Hz, 500 A, class 0.5 with harmonics up to 5 kHz.

Generating high level (as much as 50% of the fundamental) and high order (up to the 99th order) harmonics both for voltage and current represents real technological challenges.

The LNE study focuses mainly on the generation of current harmonics.

This paper describes the criteria used to design the AC fictive power source, provides the characterization of the components constituting the setup and the implementation of the necessary corrections. The results up to now are reported: a phase-fired current waveform with harmonics up to 5 kHz and 100 A effective value in the presence of 12 kV-50 Hz potential. The working axis to increase the level of the generated distorted current are also provided in this article.

2 Design of the fictive power source

The metrological qualification of the commercial EMF is currently performed in laboratories according to EN 50463-2 but using low level voltage and current inputs (hundreds of mV and mA). Thus, the customer VMF and CMF are working in the lowest part of their measurement range which can generate increased uncertainties. To overcome this inconvenient and to be as close as possible of the harsh on-board train conditions, the fictive power source is designed to generate voltage and current waveforms of 15 kV-16.7 Hz and 25 kV-50 Hz and 500 A with harmonics up to 5 kHz. The main criteria used to design this AC fictive power source are:

- Compactness (transportable on site)
- Ability to reproduce the waveform distortion
- Versatile (both voltage and current control modes are available).

The chosen principle (Fig.1) consists in creating a numerical low level distorted voltage that will be amplified and converted into current: first, by means of a high-powered amplifier, Amplifier *I,* used in current control mode and then by a wideband injection current transformer (ICT). The cable carrying the high current is mounted at high potential by means of a step up voltage transformer. Wideband current monitor sensors, calibrated instrument voltage transformer and synchronized digital multimeters constitute the reference system and allow performing accurate power and energy measurements.

The device under test (DUT in Fig. 1, usually a commercial EMF) is supplied by the generated distorted current and the sinusoidal high voltage. Its indication is to be compared to the reference system result.

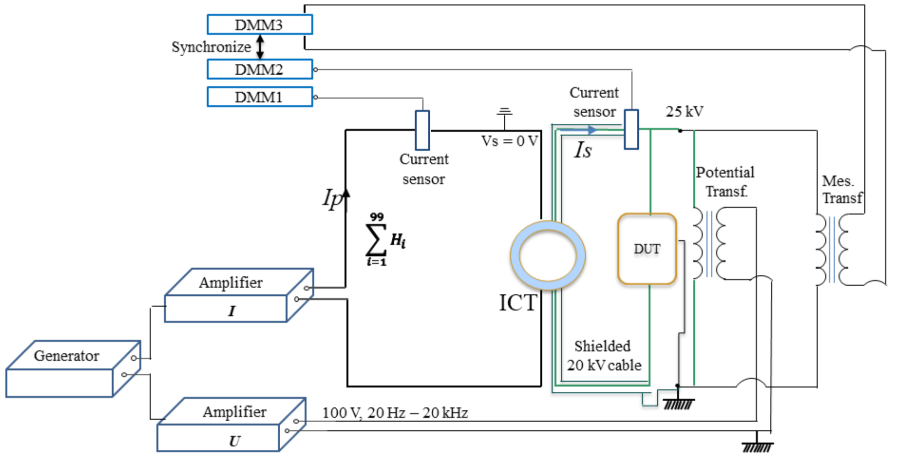

Fig. 1. Design principle of the AC fictive power source.

The high-powered amplifier *I* can operate in either voltage or current mode and features robust output devices and a power range of over 3000 watts RMS. It provides very low noise and fast slew rates, and can safely drive a wide range of resistive, inductive loads. The features are listed in Table 1.

Table 1. Characteristics of the amplifier, *I*

Specification	Value
Max Input Voltage	± 10 V balanced or unbalanced
Gain : Voltage mode Current mode	 20 V/V 20 A/V
Low output impedance	0.5 Ω
RMS output for 1 Hour, 100% Duty Cycle Voltage Current	 45 V 90 A
Frequency bandwidth	DC - 30 kHz
Phase response	± 8,3 ° (10 Hz – 10 kHz)

The wideband injection current transformer is the core of the fictive power source. The results presented in this paper are obtained with a magnetic material having linear characteristics and a 10:1 ratio. The frequency response was obtained and corrections are applied.

The reference system for the EMF calibrations consists in accurate, traceable and synchronized measurements of current and voltage. In order to reduce the influence of high voltage on the current measurement, a 20 kV shielded cable is used to supply the device under calibration. The cable sheath being at zero potential, no voltage stress is applied to the current sensor. In this way, the bandwidth, the sensitivity and the accuracy of the current sensors became the criteria more important than the withstand voltage. Current sensors with minimum 50 kHz bandwidth, high dynamics (able to detect accurately both few A and hundreds of A) with an accuracy less than few 10^{-4} are needed for this application.

3 Setup characterization

Since the elements used to constitute the fictive power source are not perfect, it is necessary to measure (during the characterization phase) the differences between the measured and the targeted signals. The use of mathematical tools should make possible, subsequently the corrections of the identified differences.

3.1 Current sensors

The setup relies on the use of Pearson type current monitors. The sensor used for the results reported in this paper is a 101 model and presents the following characteristics:

- Sensitivity: 10 mV/A;
- Maximum RMS current: 200 A;
- 3db cut-off bandwidth: 0.25 Hz – 4 MHz.

The calibration of its conversion coefficient, K_P (mV/A) was performed in the electrical metrology laboratory with ± $1 \cdot 10^{-3} \cdot$ K_P expended uncertainty (k = 2).

Fig. 2 illustrates the linearity with the input current (53 Hz, sinusoidal current), while Fig. 3 shows the frequency response obtained at 3 A level. As it can be noticed, the linearity of the conversion coefficient is $1.07 \cdot 10^{-4}$ from 3 A to 120 A, the $6.26 \cdot 10^{-4}$ from 0.5 A to 120 A. Therefore, both fundamental and harmonics components are reproduced within

$6.26 \cdot 10^{-4}$ without specific amplitude corrections. No phase displacement in the limits of the uncertainty was observed.

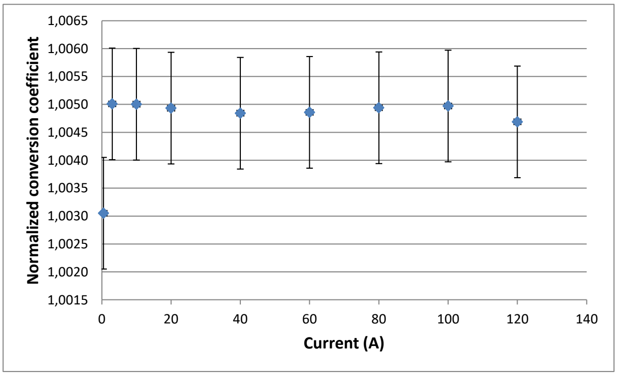

Fig. 2. Linearity of current sensor relative to input current

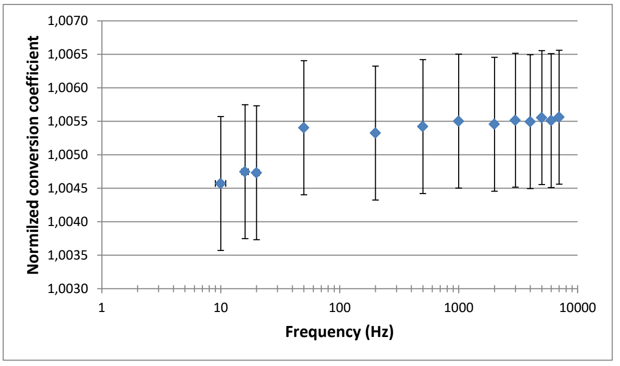

Fig. 3. Frequency response of current sensor

The standard deviation of the conversion coefficient of the current sensor from 10 Hz to 7 kHz is $3.6 \cdot 10^{-4}$. Therefore, the 50 Hz value will be used during the further measurements and the standard deviation will be considered in the uncertainty budget.

3.2 High current generator

The characterization of the current generation part is performed by comparing the current (I_S in Fig. 1) to the voltage applied to the input of the high-powered amplifier (Amplifier *I* in Fig. 1). The generated current was measured by means of Pearson 101 sensor, while the input voltage was generated by a calibrator. The response of this characterization is given in Fig. 4 for the gain variation, respectively in Fig. 5 for the phase displacement.

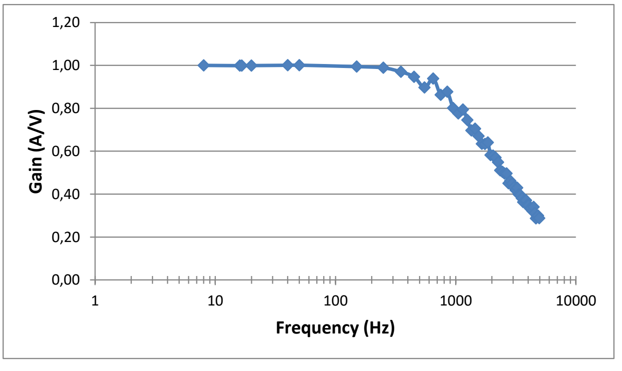

Fig. 4. Gain variation with frequency

It can be noticed that frequencies higher than 1.45 kHz are attenuated with more than –3 dB. Moreover, an increasing phase shift with the frequency is introduced.

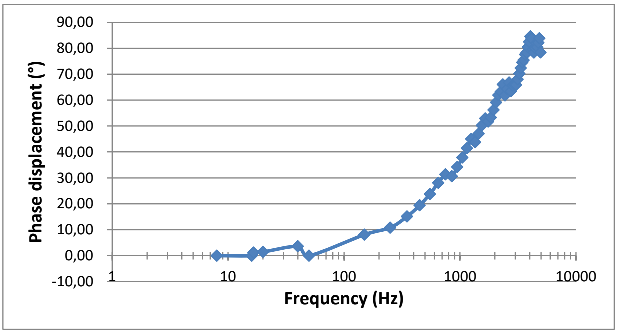

Fig. 5. Phase displacement variation with frequency

Both high-powered amplifier and the magnetic material of the injection transformer disturb the input signal. Consequently, corrections are implemented as described in the following section.

4 Results

The ECF shall be tested for the influence of odd harmonics. The EN 50463-2 standard defines the phase-fired waveform for 50 Hz up to 21st order harmonic. Starting from this definition, we added harmonics up to 99th order with decreasing amplitude from 3% to 1% of the fundamental.

The Discrete Fourier Transform (1) is used to link temporal representation to the frequency one. We used 256 samples for one cycle.

$$S(f) = \sum_{n=0}^{N-1} S(nT) \cdot e^{-i2\pi f nT} \qquad (1)$$

Fig. 6 shows the defined test waveform and its harmonic content is in Fig. 7.

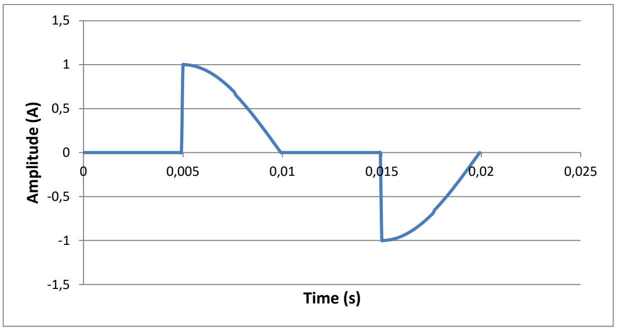

Fig. 6. Phase-fired waveform at 50 Hz

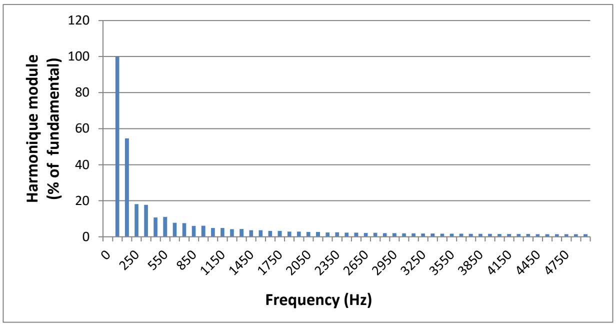

Fig. 7. Harmonic content of phase-fired waveform

This phase-fired waveform represents the current aimed to be applied to the DUT. Since the current generation part introduces distortions, we implemented the necessary corrections as described in the following.

The amplitude of each harmonic composing the defined phase-fired waveform was multiplied by a factor obtained during the characterization of the gain variation. The phase of each harmonic was corrected by extracting the value of the phase displacement determined during the characterization step from the phase value provided by the standard.

New values for amplitudes and phases defining the odd harmonics are, thus, obtained. The Inverse Fourier Transform allowed getting the discrete corrected waveform to be generated.

The measured current and the phase-fired waveform as created according to the standard are plotted in Fig. 8.

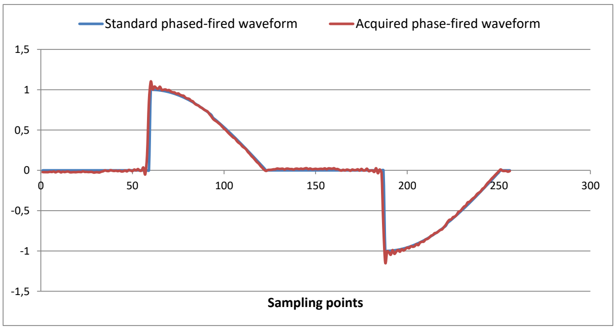

Fig. 8. Measured and standard phase fired waveforms

The implemented fictive power source allowed the generation of a phase-fired current waveform with 100 A effective value and harmonics content up to 5 kHz raised at a potential of 12 kV, 50 Hz. The implemented corrections compensate the attenuations introduced by the current generation part of the setup. This is shown in Fig. 8, the acquired and the ideal waveforms fit well, without phase displacement or attenuation of the shape.

The high-powered amplifier was used in current control mode with 20 V/A gain, the Injection Current Transformer (ICT) was based on linear magnetic material with a ratio of 10:1 and the impedance of the secondary loop was 2.5 mΩ.

5 Conclusions

Several challenges appear when generating such important harmonics. The most sensitive component is the injection current transformer. To optimize the operation point, a compromise has to be found between the transformation ratio, the impedances of the primary and secondary circuits as well as the power supply mode of the transformer in order to avoid saturation of its magnetic core.

Among the critical parameters, one can list the magnetic properties of the injection transformer. The main issue is that there are not really known since magnetic properties change with thermal and mechanical treatment, with the frequency, too.

Our approach is to test two types of magnetic materials: those with linear, respectively non-linear magnetisation curve. Each type has some advantages and inconvenient parts.

The materials with linear magnetization curve can be controlled in open loop and a direct ratio between the injected and the output current can be established.

The non-linear magnetization curve types of materials are more easily found on the market and impose voltage control rather than current control. However, the impact of the secondary loop impedance is higher and its nature and value have to be carefully designed and considered. Additionally, their control requires the implementation of a closed loop based on the secondary current measurement.

Other critical parameters with influence on the operating point of the injection current transformer are its ratio and the impedance transfer.

Our approach is to reduce the ICT ratio, the secondary loop impedance and choose the appropriate control mode.

In order to avoid the saturation of the ICT, a balance has to be found between the supply signal (type: voltage or current and level) and the secondary loop impedance. One has to consider that the impedance of the secondary loop is transferred to the primary with the square of the ICT ratio. Lower (impedance, ratio) the better. The issue here is that the secondary loop contains the EMF to be calibrated, which involves adding in the setup an unknown impedance. A solution is to reduce the cable impedance acting on all parameters: length, material resistivity, section. However, attention has to be paid to the length of the cable since on-board calibrations are planned.

Concerning the supply voltage, it has to remain conform to Boucherot formula (which establishes a link between the sinusoidal voltage at the terminals of a winding wound around a magnetic circuit and the magnetic field within this circuit) and stay under the amplifier characteristics that are limited in voltage (up to 45 V) .

Today, the limitation in terms of distorted current generation is 100 A effective value. We are working currently to the design of a new injection transformer that allows reaching the target objective of 500 A.

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