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IN-HOUSE TEST OF LOW FREQUENCY CONDUCTED EMISSIONS OF STATIC CONVERTERS FOR RAILWAY APPLICATION

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Abstract – The test and calibration setups are presented for the measurement low frequency conducted emissions of rolling stock and on-board static converters. The work is aimed to allow the laboratory or factory test of static converters without the need of long and expensive runs on a locomotive on a real line. The post processing needed for statistical evaluation of emissions is also presented.

Keywords: Guideway transportation power systems, Power system harmonics, Electromagnetic compatibility

1. BASIC INFORMATION

The increasing complexity of railway systems requires the accurate analysis and the evaluation of the compatibility of the electrical system with respect to the normative standards and operator's regulations [1-5]. In particular, when a new traction vehicle is introduced on existing lines it is essential to ensure that the vehicle and the signalling systems are compatible under normal operating and failure conditions. In general operators specify emission limits (the so called "limit mask") for the locomotive traction current absorbed through the pantograph on a given frequency range; additional limits exist for single on-board equipment (like auxiliary converters) and these limits are often specified as a given fraction of the pantograph limits, so that it is ensured that the sum of the conducted emissions from each on-board equipment cannot be larger than the limits specified for the pantograph current.

In many cases there are several equipment and configurations which can accomplish/perform the required measurements: for the measurement of low frequency conducted emissions through the pantograph the choice may be on the current probe (full scale, accuracy, frequency range), on the type of filtering, if necessary, and on the acquisition equipment (either time domain or frequency domain). It is important indeed to translate operators' requirements into measurement system specification, in order to demonstrate the suitability of the adopted setup.

Moreover, since it is possible that during transients (like load step changes, pantograph bounces and consequently step changes of the supply voltage, wheel skidding, etc.) one or few spectrum components violate the specified limits, but the time duration and the probability of occurrence of the violation is small enough not to interfere seriously with any signalling device, some operators have added a statistical evaluation of the conducted emissions of the equipment under test. This is an additional requirement for the post-processing software, which must not only comply with operator's regulations but also help the designer and test engineer in locating worst case conditions and critical configurations.

Finally, an important factor in the definition of the test setup is the correct positioning and the design of the ground connection of the measuring equipment. Since the equipment under test is a medium (or large) power static converter or even an entire locomotive, stray magnetic fields from cables and inductors and their coupling with signal cables and ground loops are of great concern. This aspect is treated in the following section.

2. MEASUREMENT SETUP

In Italy low frequency conducted emissions are regulated by the Italian railways standards FS96 [2]. Not only the emission limits are indicated, but also the procedure for data post-processing and computation of statistical indexes and the measurement equipment to be used.

The FS96 approach is towards frequency domain analysis by means of an FFT analyser (to reach the minimum frequency of 3 Hz) with PC interface for data storage. The indicated current probe is conceived to be placed directly on the pantograph line, so that it is a current transformer with sufficient air-gap to avoid saturation due to the large amplitude of the dc component of the absorbed traction current. The performance of such current transformer was tested on an available item and it was found very noisy. In our application the dc current absorbed by the converter under test is less than 25 A and it is only a fraction of the normal traction current for which the current transformer was designed. Furthermore, the limits applied to auxiliary converters are derived by reduction to 1/64 of those specified in the FS96 (see Fig. 1).

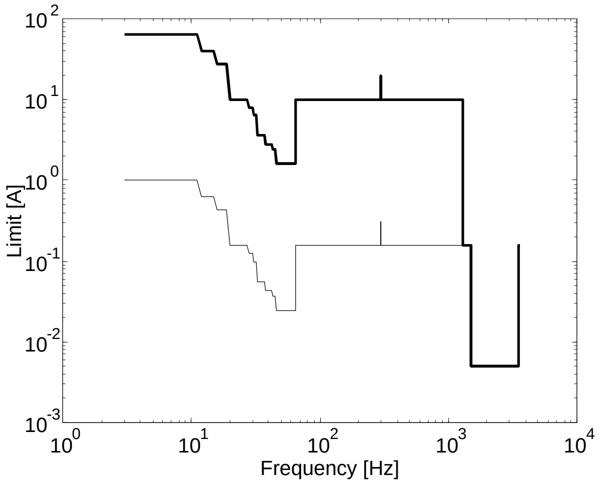

Fig. 1. Limits for traction current (heavy solid) and auxiliary converters current (thin solid) (as per FS96)

The doubling of the limit at 300 Hz is due to the presence in the absorbed traction current of a particularly large 300 Hz component produced by Electric Supply Substations 6-pulse rectifiers.

So the current probe used for the tests is a clamp-on probe with higher sensitivity and less output noise; the used model is a Textronix A6303 with 100 A maximum dc rated current.

Measurements are performed in the time domain, to allow the maximum flexibility for post-processing; the Textronix probe is interfaced through an amplifier (Textronix AM503) directly either to a digital storage oscilloscope or to a (PC hosted) digital acquisition board.

The focus is on the definition of the minimal characteristics of the measuring system to perform the required tests with sufficient accuracy. The sensitivity of the measuring system is determined by the minimum detectable line current level L_m, corresponding to the lowest current limit, which for the 1500 – 3500 Hz frequency range is only 5 mA rms (see Fig. 1). L_m together with the full scale value FS set on the amplifier during tests determines another requirement for the quantization error q of the Digital Acquisition System (DAS): $q < L_m/FS$. The FS setting shall not consider the amplitude of the dc component of the line current absorbed by the converter under test; only the ac ripple is significant, so that the probe may be ac coupled to the DAS. Attention must be given to the standard ac coupling of oscilloscopes; a few tests with a square wave at low frequency can demonstrate if the low corner frequency is small enough for the required bandwidth (3 Hz for the FS96 standard). During our tests FS was set to 800 mA pk, so that even an 8 bit acquisition system can strictly meet the requirement, but a 12 bit system is suggested.

The DAS sampling rate should meet in principle the Shannon rule, being at least slightly larger than twice the bandwidth B_S of the input signal. The input low pass filter (introduced for anti-aliasing purpose) sets the B_S value to 4 kHz, nearly 10% larger than the FS96 requirement. The minimum sampling rate was set to 25 kS/s (6 oversampling with respect to B_S), in order to increase the S/N ratio.

The performances of the measurement system are reported in Table I; the accuracy was tested using the setup shown in Fig. 2.

TABLE I. Measurement system performance

Current probe (Tektronix A6303)	
Bandwidth	3 Hz – 10 MHz
Noise at amplifier input	< 3 mA
Amplifier (Tektronix AM503)	
Output noise voltage	< 0.8 mV
Digital acquisition system	
Resolution	8 bit or higher
Sampling rate fs	25 kS/s or higher

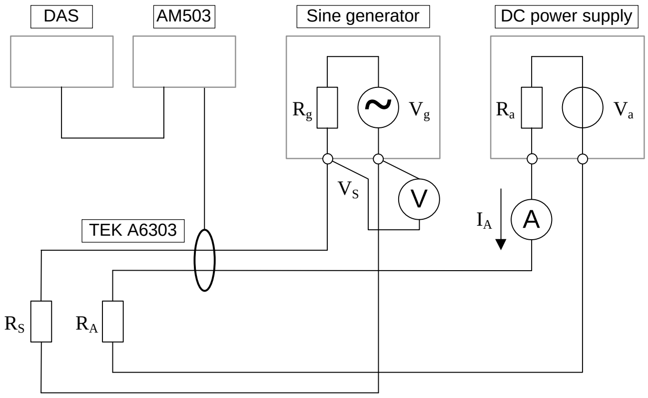

Fig. 2. Calibration setup

The signal voltage V_S is measured with a true rms voltmeter, periodically calibrated, with an accuracy for rms measurement in the 1-10 V range equal to 0.5%. The value of the signal current I_S is obtained by ratio of the measured voltage V_S with two precision resistors (998.5 and 99.6 ohm, measured at 25°C with accuracy equal to 0.2%) used for the two current levels of 10 mA and 70 mA respectively.

The rms value I_S* measured by the DAS through the probe amplifier is affected by the composite inaccuracy given by the voltage noise at DAS input and the quantization error. The output level of the probe amplifier (the full scale range is about ±50 mV) isn't large enough to neglect the first source of inaccuracy in favour of the second one. The dc power supply superimposes a dc current component I_A to the signal current I_S and it is regulated by the resistor R_A; the accuracy of this part of the calibration setup is not important and it is only 2%.

The tests performed for calibration are reported in Table II. The relative error *err* is simply computed as:

$$err = 100 \times \left| (I_S - I_S^*) / I_S^* \right| \quad (1)$$

It will be shown that a predominant contribution to calibration accuracy is given by the self heating of the measuring resistors and by the class of the true rms voltmeter. The power rating and the thermal drift of the resistors are carefully chosen in order to keep the resistance change due to self heating during the test low.

TABLE II. Calibration of the measurement system

Test	Signal frequency [kHz]	DC supply current I_A [A]	Signal current I_S* [mA]	Signal current I_S [mA]	Relative error *err* %
1	1	0	10.05	9.63	4.1
2	1	0	70.08	67.06	4.3
3	10	0	9.96	9.49	4.8
4	10	0	69.78	66.80	4.3
5	1	20	10.09	9.45	6.3
6	1	20	70.98	66.39	6.5

The calibration of the current probe was repeated reducing the uncertainty related to self heating of the resistor R_S; R_S is 234.2 ohm with 1W rated power; the 2.5 mA rms IR current delivers only 1.5 mW, so that the resistance may be considered constant. A more accurate rms voltmeter was used (HP 34401) with 0.06% accuracy. The results are reported in Table III.

TABLE III. Calibration of the measurement system (repeated)

Test	Signal frequency [kHz]	DC supply current I_A [A]	Signal current I_S* [mA]	Signal current I_S [mA]	Relative error *err* %
10	0.1	0	2.492	2.50	0.3
11	20	0	2.49	2.53	1.5

An important subject is the correct positioning and connection of the measuring equipment. Since in our case the equipment under test is a medium power static converter with commutated currents of tens or even an hundred of Amps flowing into busbars and inductors, coupling of stray magnetic fields with signal cables and ground loops is of great concern. Signal cables are all shielded twisted pair and coaxial cables, so induced differential disturbance may be neglected. What must be carefully designed is the complex geometry of ground connections: some sensors may need a ground connection (a shielded current transformer, for instance), acquisition equipment may or may not have the choice for grounded/floating input, all the devices or instruments of the measurement chain have a power chord with ground pin (unless they are battery operated). It is of utmost importance that the ground connections associated with power chords are bundled and packed together, since in authors' experience a current as high as 100 mA may be induced into two 1 m long power chords coming from two piled up instruments and connected to the same plug without any attention to cable routing. Two piled up instruments may close the ground loop by intentional connection of their "signal grounds", if their metallic chassis are accidentally in contact or by inductive/capacitive coupling of their internal circuitry (in particular ground buses). The thing was observed even for an unused (switched off but still connected through its power chord) instrument; some experiments showed that the good orientation (which depends on internal circuits disposition) may attenuate external disturbance on the DAS input by a factor of 2 to 5. So, orientation and separation of used measurement equipment and removal of unused instruments may be again a useful way to mitigate unwanted external disturbance.

3. POST-PROCESSING

The spectrum of the digitized time domain waveforms is calculated using Short Time Fourier Transform (STFT) algorithm [6-8]. A variable window overlap (usually set to 50%) may be used to reduce any sudden change of spectrum components. The FS96 standard indicates that each spectrum used for successive statistical processing must be the result of the average of the spectra computed over 3 seconds of waveform recording.

The FS96 standard subdivides the considered frequency range (0–3600 Hz) into two intervals (0-400 Hz and 400-3600 Hz) and indicates also two different frequency resolutions (1 Hz and 8 Hz for the two intervals respectively); it seems that this is suggested by the need to keep the number of spectrum components equal to 400. In the present procedure the frequency resolution is kept to its maximum (1 Hz), so that the number of spectrum components is N=3600, a unique spectrum is computed for each signal window and the window length for STFT is T_w=1 s. Each spectrum is stored for successive statistical analysis.

As stated in the FS96 standard, the limits shown in Fig. 1 (identified by the letter L) are multiplied by a set of coefficients to obtain a family of curves, which define suitable amplitude intervals. A limit P_i on the relative frequency of occurrence of each spectrum component p_i is associated to each interval as reported in Table IV.

TABLE IV. FS96: Amplitude intervals and relative frequency of occurrence

Index	Amplitude interval	Relative frequency limit P_i
1	I < L	1
2	L < I < 1.5 L	0.0777
3	1.5 L < I < 1.75 L	0.00262
4	1.75 L < I < 2.5 L	$3.46\ 10^{-5}$
5	2.5 L < I < 3.5 L	$7.96\ 10^{-11}$
6	I > 3. 5 L	0

It is then computed the number of spectrum component M_i belonging to each specified interval. The relative frequency for each interval is then computed and compared with the limits reported in Table II. The test is successful if

$$p_i \le P_i \quad \forall i \qquad (2)$$

An additional condition on the quantity

$$FPA = \sum_{i=2}^{5} p_i / P_i \le 1 \qquad (3)$$

is specified: if FPA≤0.1 the test is successful and no other test is necessary; if 0.1<FPA≤1 additional tests are necessary; if (2) holds then FPA cannot be greater than 1.

4. APPLICATION EXAMPLE

The described procedure was applied to the test of a 45 kVA static converter, operating at 56.5 Hz output frequency and supplied at 2300 V dc. The tests were performed in different operating conditions. The time duration of each operating condition (either transient or steady state) to the total duration of tests is not always clearly indicated and must be decided for the specific converter under test. A reference of general applicability is the standard UIC 550-2 [9]. Attention must be given to the definition of transients (like load and supply voltage step changes); they produce a family of transient low frequency harmonics almost always above limits.

An example of the computed spectra is shown in Fig. 3.

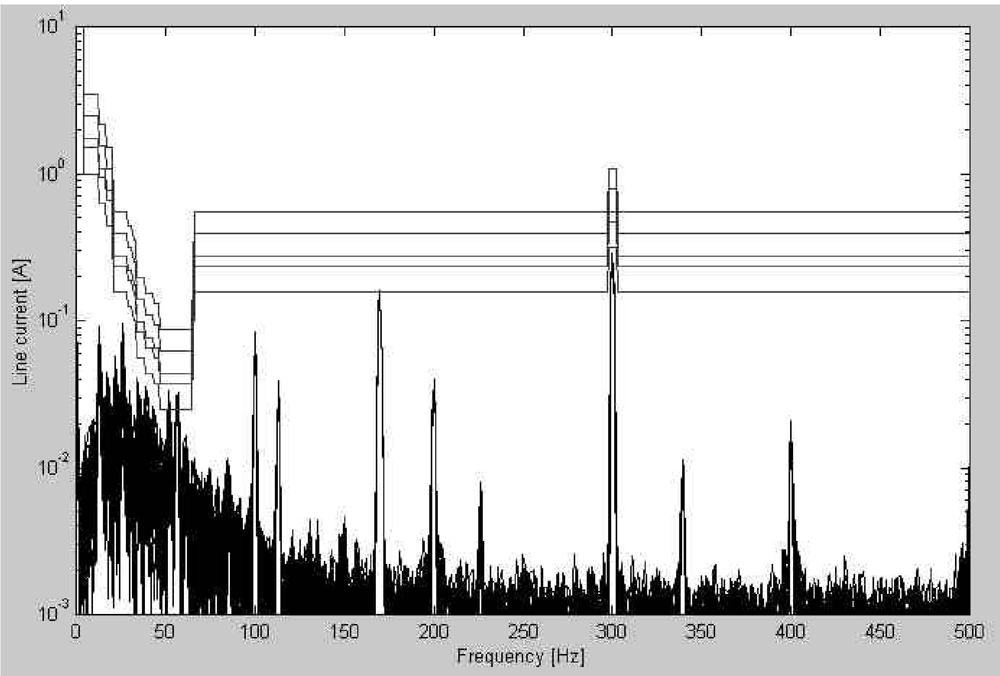

Fig. 3. Example of conducted emissions (restricted to 0 – 500 Hz frequency range)

Some spectrum components, responsible for increasing p_2 (the relative frequency index of the 2nd amplitude interval), are in reality produced by the dc supply system (6-pulse diode rectifier). It is not uncommon that supply harmonics are larger than converter emissions; in this case they must be filtered before any test take place, since it is impossible to eliminate them "a posteriori" from the measured data. In our example a 1000 uF capacitor at the rectifier output terminals reduced the characteristic harmonics by about an order of magnitude.

The spectrum components generated by the converter under test are the output frequency component at 56-57 Hz, which appear in the 2nd amplitude interval, the third harmonic at 170 Hz and the sixth harmonic at 340 Hz

4. CONCLUSION

A procedure for the measurement of low frequency conducted emissions from static converters for railway applications is presented. The accuracy of the measurement chain is evaluated with a calibration setup with an expanded uncertainty of less than 1%. Measurements are performed in time domain to ensure higher flexibility for post-processing; the railway operators' standards often require a statistical analysis of spectrum components distribution with respect to a family of limit curves. The presented measurement and calibration setups are intended to be used at the manufacturer laboratory to demonstrate compliance to standards with sufficient accuracy without the need for expensive and time consuming tests on-board a locomotive on a real traction line.

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