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EVALUATION OF THE DYNAMIC BEHAVIOUR OF HEAVY CURRENT SHUNTS

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Abstract − A method for the assessment of the dynamic behaviour of heavy current shunts is described, which is based on the evaluation of the shunt frequency response through spectral analysis of input and output measured signals. The method has been tested by applying it to simulated current impulses and experimented in the case of a pulse current, generated by the discharge of a cable capacitance, measured by a thin walled coaxial-tube shunt.

Keywords: shunts, heavy-currents, dynamic behaviour.

1. INTRODUCTION

High power laboratories are required to generate and measure heavy currents, in order to carry out tests for the qualification of electromechanical components. The measurement of these currents, which can reach values of hundred kiloamperes and last from some to hundreds of milliseconds, is made difficult by the presence of strong magnetic fields, electrodynamics forces and dissipative effects, generated by the currents themselves.

While the tests to be carried out are fully defined in specific standards, little information is given about the characterisation of the measuring systems; however, the high power laboratories have to assure traceable calibrations of their measuring systems in order to operate according to the ISO/IEC 17025 "General competence of testing and calibration laboratories". Calibration of the current transducer, which generally consists of a Rogowski coil or, more often, of a resistive coaxial-tube shunt, is usually performed at power frequency by comparison with standard current transformers at values not higher than some kiloamperes. DC calibration is also carried out in the case of the shunts.

Taking into account that the frequency spectrum of the heavy currents may include components up to several ten kilohertz, the behaviour of the transducer in the frequency range of interest should be determined.

The evaluation of the dynamic behaviour of coaxial thin walled or compensated shunts (Fig. 1) is complicated by their constructive characteristics, very low resistive value and wide operating range [1]. The shunt dynamic behaviour can be determined by different methods such as analysis of the current step response and measurement of the shunt impedance. Both these methods are not easy to be implemented and are characterised by drawbacks and limits, as evidenced in [2].

In the paper, a method is described and discussed, which is based on the evaluation of the system frequency response from spectral analysis of input and output measured data, in the case of transient current signals with wide frequency content. The proposed approach has been tested by applying it to the analysis of simulated current impulses and then experimented in the case of a capacitor discharge current, measured by a thin walled coaxial shunt.

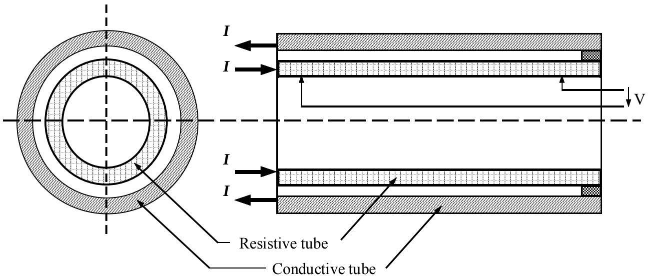

Fig. 1. Coaxial-tube shunt: front and lateral sections.

2. THE EVALUATION OF THE SHUNT DYNAMIC BEHAVIOUR

2.1 Measurement of the shunt impedance and current step response

The determination of the dynamic behaviour of a heavy current shunt by evaluation of its impedance as a function of frequency requires the generation and measurement of stationary currents of sufficiently high amplitude in a quite wide range of frequencies. Fig. 2 shows the measured magnitude of the impedance variation of a coaxial thin walled 1 mΩ shunt in the frequency range from 20 Hz to 20 kHz. The applied currents (some ten amperes) are significantly lower than the rated ones and because of the shunt low resistive values, from some ten microohms to some milliohms, the voltage across the transducer can be significantly affected by noise. Damped sinusoidal currents up to some kiloamperes generated by a capacitor discharge at frequencies up to some kilohertz can be used, provided that a reference current measuring system characterised for the considered frequencies and currents is available.

Information about the behaviour of the transducer at higher frequencies can be obtained by measurement of the step current response of the system. However, high current steps with constant amplitude, lasting for a sufficient long time, can hardly be generated. The evaluation of the response time parameter allows the determination of the frequency response when the transducer can be consider a first order linear system, such as in the case of the thin walled shunt.

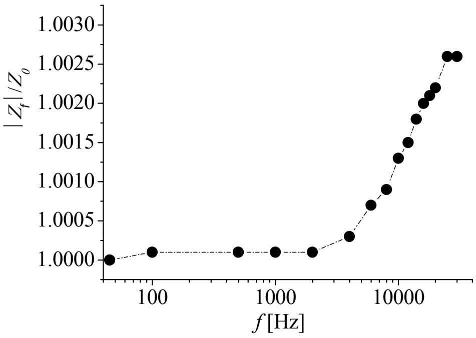

Fig. 2. Impedance variation of a thin walled shunt.

2.2 Evaluation by DFT

An alternative approach is the evaluation of the shunt frequency response *H(f)* from the discrete Fourier transform (DFT) of input and output transient random signals $x(t)$ and y(t). The input $x(t)$ is assumed to be measured by a current measuring system with ideal behaviour, while y(t) is the output given by the shunt under characterisation.

The magnitude of $H(f)$ can be expressed as ratio between the transient cross spectral density function $\mathcal{G}_{xy}(f)$ of the input $x(t)$ and output $y(t)$ and the energy spectral density function $\mathcal{G}_{xx}(f)$ of the input $x(t)$ according to [3]:

$$|H(f)| = \frac{|\mathcal{G}_{xy}|}{\mathcal{G}_{xx}} \tag{1}$$

The energy spectral density function $\mathcal{G}_{xx}(f)$ and the cross spectral density $\mathcal{G}_{xy}(f)$ are respectively defined, for non negative frequencies only, as:

$$\begin{aligned} \mathcal{G}_{xx}(f) &= TG_{xx}(f) = 2E\left[|X_k(f)|^2\right] \\ \mathcal{G}_{xy}(f) &= TGxy(f) = 2E\left[X_k^*(f)Y_k(f)\right] \end{aligned} \tag{2}$$

where $G_{xx}(f)$ and $G_{xy}(f)$ are the one sided power spectral density functions [3], T is the record length, $X_k(f)$ and $Y_k(f)$ are the Fourier transforms of the sample signals $x_k(t)$ and $y_k(t)$ respectively.

The best estimations of $\mathcal{G}_{xx}(f)$ and $\mathcal{G}_{xy}(f)$ are obtained by averaging over an ensemble of estimates computed from a series of n_p independent input-output measurements carried out under the same conditions:

$$\hat{\mathcal{G}}_{xx}(f) = \frac{2}{n_p}\sum_{k=1}^{n_p} \left|X_{k_d}(f)\right|^2$$

$$\hat{\mathcal{G}}_{xy}(f) = \frac{2}{n_p}\sum_{k=1}^{n_p} X_{d_d}^*(f) Y_{k_d}(f) \tag{3}$$

where $\hat{\mathcal{G}}_{xx}(f)$ and $\hat{\mathcal{G}}_{xy}$(f) are the estimates of the energy spectral density functions and $X_{kd}(f,T)$ and $Y_{kd}(f,T)$ are the DFT of the k_{th} input and output signals, recorded with a record length $T \geq T_1$, being T_1 the time range where the random process is significantly different from zero.

A quantitative indication about the "error" in the estimation $|\hat{H}(f)|$ of the shunt frequency response through (1) and (3) is obtained from the coherence function $\gamma_{xy}(f)$ between the measured input and output, which can be interpreted as the fraction of the output spectrum of $y(t)$ that is linearly due to $x(t)$ at the frequency f. The coherence function $\gamma_{xy}(f)$ is defined as:

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)} \tag{4}$$

and results equal to unity in the ideal case of x(t) and y(t) completely correlated. Extraneous noise, non linearity of the system and presence of other inputs besides $x(t)$ can lead to a coherence function less than unity.

The estimate $|\hat{H}(f)|$ may be affected both by systematic and random errors. For a linear system, systematic error can be considered negligible if no significant noise is present at the input measurement, which does not pass through the system, and if the resolution bandwidth is sufficiently narrow. The normalised random "error" associated to $|\hat{H}(f)|$, which is defined as the standard deviation of the estimate above its expected value, can be determined as a function of the coherence function and the number n_p of independent input-output measurements according to:

$$\sigma_r\left|\hat{H}((f))\right| = \frac{\left[1-\hat{\gamma}_{xy}^2(f)\right]^{1/2}}{|\hat{\gamma}_{xy}(f)|\sqrt{2n_d}} \tag{5}$$

3. TEST OF THE METHOD

A current impulse $i_a(t)$, generated by the discharge of a capacitance through an inductance, was simulated with maximum amplitude 4.5 kA, rising time 5 µs and discharge time of about 50 µs and its harmonic content obtained by DFT. A current transducer with a known imposed first order transfer function was considered and the output signal $i_b(t)$ was then calculated (Fig. 3).

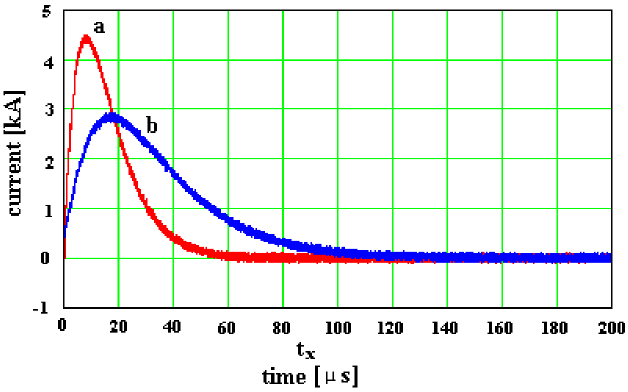

Fig. 3. Simulated currents with added noise:
a) input current; b) output current.

In order to reproduce the actual signals, 1% random noise was added both to the input and output current impulses. A series of n_p couples of input and output signals (sampling frequency f_s= 50 MHz, sample number N=32000) was simulated and the energy spectral densities were obtained according to (3).

The magnitude of the frequency response was then calculated (1), together with the related coherence function (4) and compared to the simulated one. At the increase of n_p, the calculated response closely reproduces the imposed one and the coherence function approaches to unity. Fig. 4 shows the comparison between "true" (dots) and calculated (dashed line) frequency response, in the case of n_p=5.

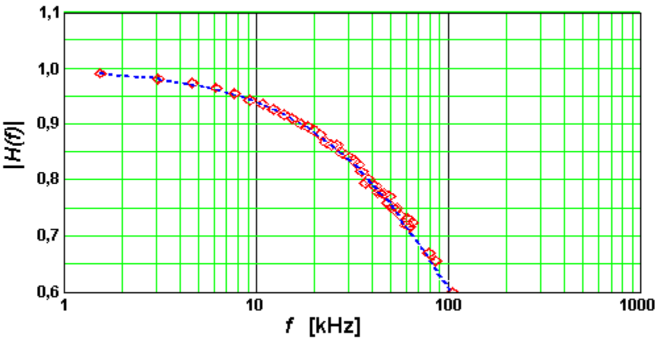

Fig. 4. Comparison between computed (dots) and imposed (dashed line) frequency response.

4. APPLICATION OF THE METHOD

The method has been then experimented in the characterisation of actual devices. The current generated by the discharge of a coaxial cable capacitance was simultaneously applied to a thin walled current shunt, with resistance 1 mΩ and rated current 5 kA for 1 s, and to an input current measuring system.

An impulse current transformer was used as input current measuring system, which essentially consists of a toroidal coil with a magnetic laminated core, wounded across the primary conductor. Because of core saturation, leading to a distorted output waveshape, and internal dissipation limits the impulse current transformer cannot be used for the measurement of heavy currents lasting hundred milliseconds, which are typical of short-circuit tests. However, because of its wide bandwidth, it can be conveniently adopted for the measurement of relatively high currents of short duration, such as those generated by discharge of a cable capacitance [4]. A further advantage is represented by the fact that the transducer is physically separated from the test circuit.

Fig. 5 shows a scheme of the test circuit where V is the DC voltage supplied by a high voltage generator, R_d is the charge resistor, Z is the coaxial cable impedance, L is the circuit impedance, S is the spark gap device, R_x represents the shunt under characterisation and T_c is the reference current measuring transducer (bandwith=20 MHz). The length of the cable was 800 m with Z = 50 Ω. Both the voltage across the shunt and the impulse transformer output were recorded by means of a digital oscilloscope of suitable characteristics [5].

The comparison between the current $i_a(t)$ measured by the impulse transformer and that ($i_b(t)$) obtained from the thin walled shunt dividing the voltage across the shunt by the resistance value R_x is shown in Fig. 6, in the case of the first 8 μs of the coaxial cable discharge current. After the first microseconds the current behaviour shows periodic damped reflections (Fig. 7) for about 400 μs, leading to the presence of peaks and notches in the corresponding frequency spectrum.

Five acquisitions of the voltage across the shunt and the impulse transformer output were performed with record length T=500 μs and sampling frequency f_c= 50 MHz. The estimate of the frequency response and the evaluation of the coherence function were then obtained, following the procedure described, by applying relationships (1) to (4).

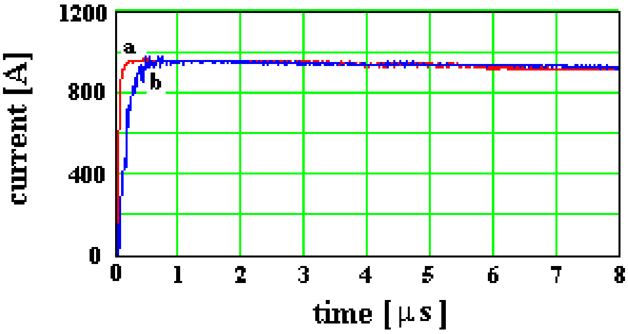

Fig. 6. Measured current in the first 8 μs:
a) impulse current transformer,
b) thin walled shunt

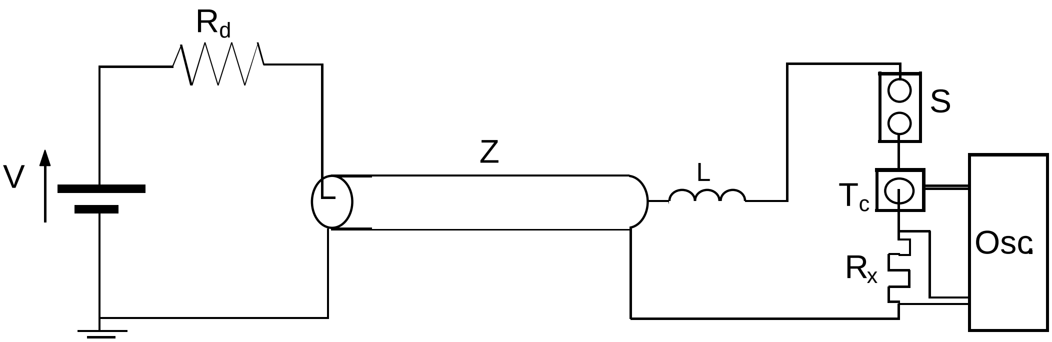

Fig. 5. Test circuit.

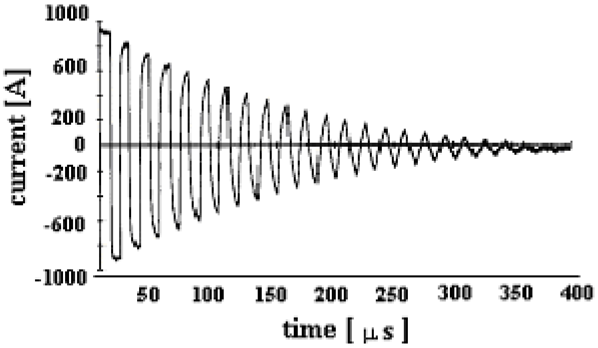

Fig. 7. Coaxial cable discharge current.

The computed response of the shunt resulted significantly altered by noise in correspondence of the frequencies which are odd multiple of the cable reflection frequency, as evidenced by the associated low values of the coherence function.

The computation was repeated by considering a new set of 5 acquisitions, carried out with higher sampling frequency (f_c=100 MHz), but with a record length limited to T'=8 μs. If the analysis is restricted to the first microseconds, the output current $i_b(t)$ can be considered as the system response to the input step current $i_a(t)$. Under the assumption that the shunt step response has reached the steady state at a time t≤T' (Fig. 6), "symmetrised" signals $i_a'(t)$ and $i_b'(t)$ can be defined over the time interval T=2T' according to:

$$\begin{aligned} i_a^{'}(t) &= i_a(t) - i_a(t - T') \\ i_b^{'}(t) &= i_b(t) - i_b(t - T') \end{aligned} \qquad (6)$$

Magnitude of the frequency response and coherence function were then calculated starting from the DFT of the symmetrised signals (6). In this case, because of the limited record length, the estimate of $|\hat{H}(f)|$ is obtained with lower resolution, starting from frequencies higher than 60 kHz.

Fig. 8 summarises the results obtained for $|\hat{H}(f)|$ by considering both the full input and output currents (square marks) and the symmetrised ones (dots). Only the values with an associated relative standard deviation of less than 1%, evaluated according to (8), have been reported on the diagram.

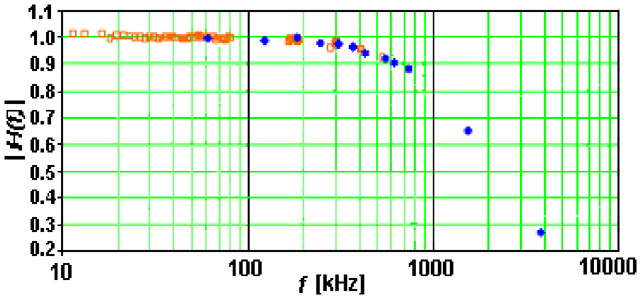

Fig. 8. Frequency response magnitude of the thin walled shunt.

Because of the different sampling frequencies and record length, information obtained by applying the method to the full and symmetrised signals is complementary and permits the analysis of the shunt dynamic behaviour over a wide range of frequencies, starting from 10 kHz. The agreement between the results obtained from the two considered waveshapes is good in the range where there is superposition of data. As expected, the obtained frequency response behaviour is that typical of a first order system.

5. CONCLUSIONS

The described method allows the evaluation of the dynamic behaviour of heavy current shunts in a wide range of frequencies with relatively high current values. It gives additional and complementary information with respect to those obtained by measurement of the impedance variation as a function of frequency and by current step response measurement.

To fully validate the method, further tests will be performed with other current transducers, such as compensated shunts characterised by lower resistance values, applying different current waveshapes.

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