Study of a Sensor for Measurements of High Amplitude - Fast Rise Time Currents in a Coaxial Cable

Felix Vega[1], Francisco Santamaria[1], Julián Herrera[1], Oscar Diaz[2], Francisco Roman[1]
[1]Electromagnetic Compatibility Research Group, National University of Colombia.
Ciudad Universitaria, Edif. 411 – LABE. Bogota, Colombia
[2] Universidad Distrital FJC, School of Technology, Bogota, Colombia.
*Email: jfvegas@unal.edu.co

Abstract: The EMC-UN research group has developed an EMC source able to produce high derivative current impulses of the order of 10^{11} A/s. This type of impulses is used to simulate the largest di/dt associated with lightning-currents. The source which has been developed in this research group is called Fast Impulse Current Generator (The Roman Generator).

In the present paper we investigate the calibration and test of a high amplitude-fast rise time current sensor in a coaxial cable. The sensor is used in the current measurements produced by the fast impulse current generator. This kind of sensor is barely reported in the literature as a voltage measurement instrument . However, in the present investigation we will apply currents with nanosecond rise time.

The sensor is an electric field probe. It is constructed with a modified SMA connector with the internal pin inserted in the coaxial dielectric like an E-field detector. The paper describes experimental tests, and calibration.

1 INTRODUCTION

This work starts out from measurement procedures proposed by Farr *et al.* in [1] where a similar sensor was developed and tested. The sensor in that report was a high voltage/nano seconds rise time instrument, applied to the output of a High Voltage Marx generator. A sensor with similar characteristics and different construction technique was developed previously by Weber *et al* [2].

In contrast with the cited works, this paper proposes a solution for the measurement of high amplitude/ fast rise time current signals in coaxial cables. The objective of this work is to improve the instrumentation to the current generator called “the Roman Generator”, developed by the EMC-UN research group.

The majority of the fast current sensors available offered by the instrumentation companies, usually have a fast rise time, high bandwidth, but a limited peak current value. The main objective of this work was to explore the possible use of the modified SMA-connector sensor (MSCS) to measure currents with the required rise time, bandwidth, and a large peak current value.

To achieve this goal, a MSCS was developed and tested. The measured signal was compared with the voltage output from a fast current Rogowski coil.

In the final section of this paper we propose an original analytical sketch to explain the function of the sensor. We expect to contribute to the discussion and study of this kind of devices.

2 EXPERIMENTAL TESTS

2.1 Fast Impulse Current Generator

The original idea of the Fast Impulse Current Generator (FICG) [3], was to reproduce the current derivative of the lightning subsequent return stroke for SPDs testing proposes.

The here used FICG is able to produce current impulses in the range of 1 to 10 kA and a rise time in the order of 10 ns, i.e. di/dt about 100 kA/µs or higher [4]. The maximum di/dt for the negative lightning discharge in the subsequent stroke suggested in [5] is 120 kA/µs.

The FICG consists of three main electrodes: the high voltage, the FE and the GND electrodes. They are coaxial symmetrically disposed with a proper insulation between them. An external top and bottom view of the FICG are presented in Fig. 1 and Fig. 2 respectively. The pulses used in this work were over-damped type. These pulses were obtained by using a 50Ω low inductance resistor in the high current path, which in different laboratory setups worked as matching impedance. The typical obtained pulse is presented in Fig. 3

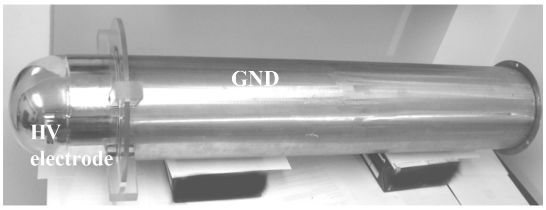

Fig. 1: External top view of the FICG. Note the acrylic insulation between the HV and GND electrodes

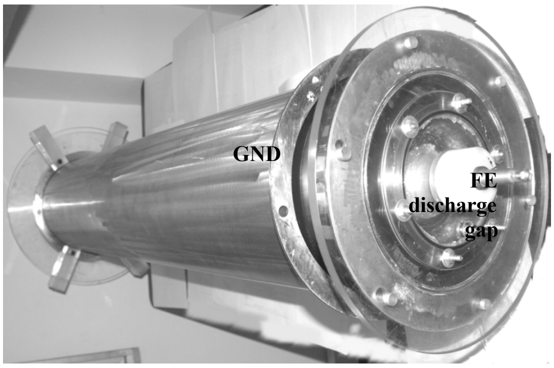

Fig. **2**: External bottom view of the FICG. The main FE and GND electrodes are unscrewed

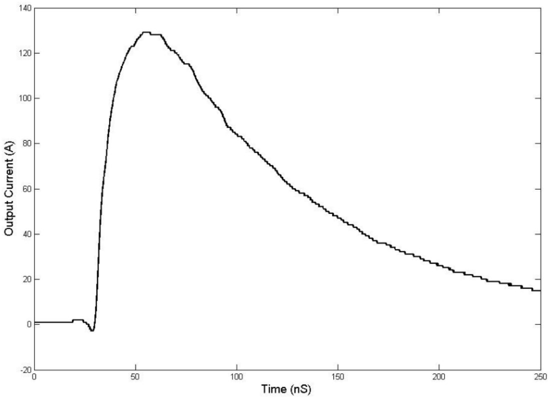

Fig. 3: Typical impulse current generated by the FICG without cable connected as a load. Only low magnitude current impulses were used in the present research work.

2.2 Modified SMA-connector Sensor (MSCS)

The MSCS is a SMA female connector with its center pin sawed-off (Fig. 4). The connector can pass through a circular hole in the Heliax external conductor. (Fig. 5). The body of the connector is held on the cable with a hose clamp (Fig. 6).

The internal conductor of the MSCS forms a capacitive divider with the Heliax internal conductor. The original signal in the Heliax cable can be recovered by integrating the MSCS output, and multiplying it by a scaling factor. The scaling factor can be determined comparing the MSCS processed signal with the reference current measured by the fast current transformer (Fig 7).

Fig. 4: Modified SMA connector (MSCS). Note the machined central pin

Fig. 5: Heliax cable with gap in the external conductor. The MSCS case in the hole drilled on the cable screen.

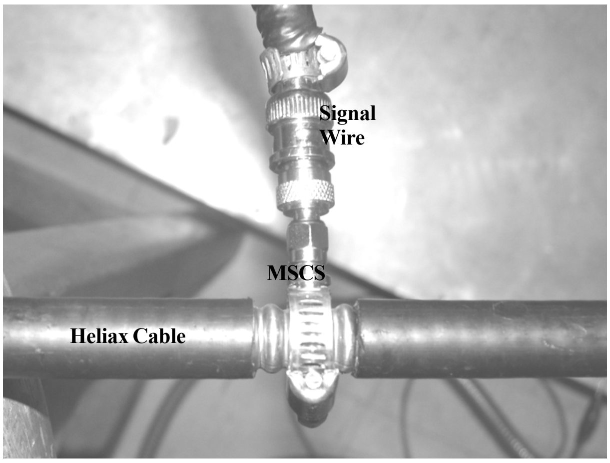

Fig. 6: Detail of the MSCS mounted on the outer Heliax layer. Note the adapter from SMA to N – connector.

2.3 Experimental Setup

The MSCS was mounted in a Heliax cable, (Ref LDF4-50A). The cable was 1m long, 12.7 mm diameter and 50 Ω characteristic impedance . One side of the cable was attached to the FICG (Fig. 8) through a Heliax N-connector (Ref L4TNM-PS). The other side of the cable was terminated in a 50 Ω resistor. This matching resistor was constructed as of the parallel connection of several carbon resistors.

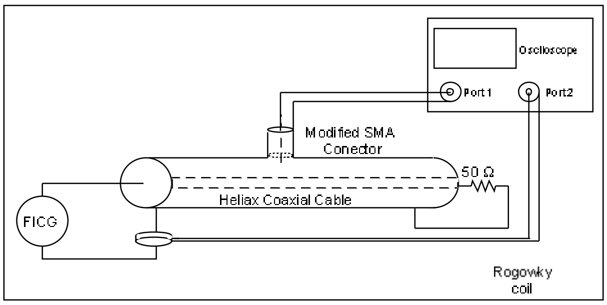

Fig. 7: Experimental set-up for the current measurement with the MSCS. Notice that the cable applied current, measured with a Rogowski coil was compared with the voltage signal obtained with the modified MSCS connector.

The FICG was energized with a high voltage DC source. The current applied to the cable was measured with a 2 GHz bandwidth, 600 ps rise time Bergoz® fast current Rogowski coil . The current and the MSCS output signal voltage were recorded in a Tektronix® TDS2022, 200MHz bandwidth digital store oscilloscope –DSO–. The 50 Ω measuring cables were shielded by using a metallic flexible duct. The DSO was powered with an uninterrupted power source (UPS). The DSO was placed in a shielding cabin. Wide copper strips were used to connect the FE discharge gap and the external GND electrode. Tests were carried out in the High Voltage Laboratory, National University of Colombia.

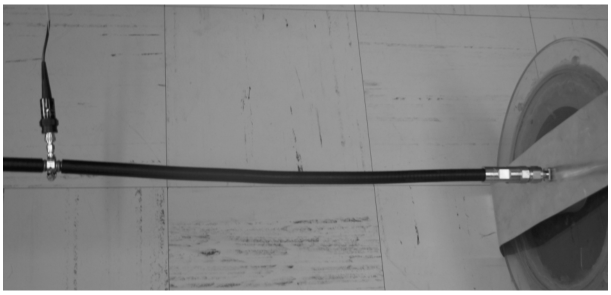

Fig. 8: Detail of the FICG output connected to the heliax cable where the MSCS was placed.

2.4 Calibration procedure.

The Calibration procedure consisted in two techniques of Network Analysis.

2.4.1 VNA Calibration procedure.

The first calibration procedure used a Vectorial Network Analyzer (VNA). The objective of this setup was to measure the Two Ports Scattering parameters of the network in frequency (S parameters). The VNA Port 1 was attached to the Heliax feeding port. Port 2 was attached to the MSCS. The other end of the Heliax cable was terminated in a 50 Ω load. Fig. 9 shows the setup.

The objective of the Two Ports S parameters measurement is to obtain a linear equation model of the transmission and reflection function of the network. The VNA obtains the S parameters in frequency domain.

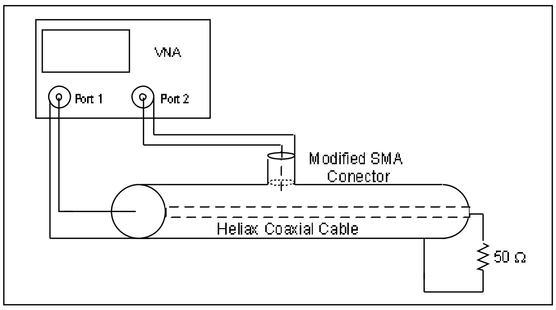

Fig. 9: VNA Calibration procedure. Experimental setup used to measured S parameters.

The Scattering parameters model consider four waves, two in the Port 1: a1, b1, and two in the Port 2: a2, b2. The waves are related by four parameters: S11, S12, S21, S22, called Scattering parameters, (S parameters), Fig. 10 illustrate it.

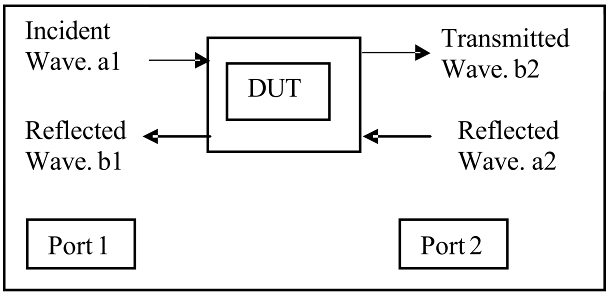

Fig. 10: Description of the S parameter model of the Device Under Test (DUT).

The two port network model is described by the following matrix relation:

$$\begin{bmatrix} b1 \\ b2 \end{bmatrix} = \begin{bmatrix} S11 & S12 \\ S21 & S22 \end{bmatrix} \begin{bmatrix} a1 \\ a2 \end{bmatrix}$$

The Network transfer function from Port 1 to Port 2 is quantified by the S21 parameter. The frequency response of this parameter permits the verification of the derivative behaviour of the MSCS sensor. This parameter is the key of the calibration procedure. With the other S parameters it's possible to adjust the measurements when impedance mismatch between the network and the generator is present.

The VNA used in the calibration procedure is the Agilent E5062A vector network analyzer (VNA) with a frequency range of 300 kHz to 3 GHz. The resultant scattering parameters are shown on Fig. 11. It can be seen that up to about 200 MHz the S_{21} transmission parameter shows a linear behaviour with frequency. At about 250 MHz, spurious responses begin to cause distortion on the response spectrum.

The calculated group delay of the MSCS was 26.0 ns over the entire VNA frequency span. This time delay must be removed from the measured voltage from the sensor for time correlations with other signals.

The coupling coefficients of the input and output ports of the sensor, represented by the S21 and S12 parameters, are conveniently low (below 0.002, that is, -54 dB) on the frequency range of interest. It can be concluded that the partial modification of the outer conductor barely perturbs the measured signal. This low coupling coefficient is the key factor in isolating the delicate instruments from the high voltage system under measurement. It also simplifies the calculation of the measured quantity as no reverse coupling effects should be accounted for.

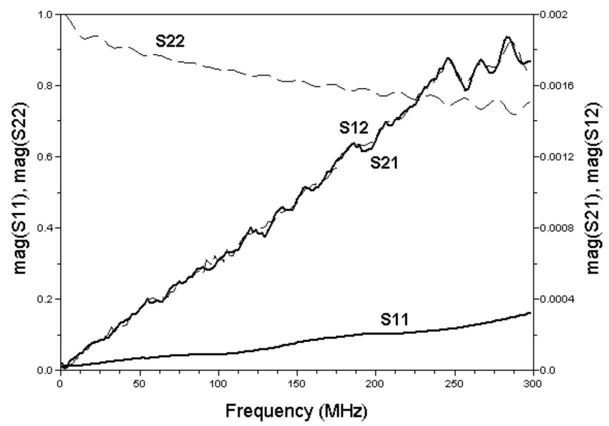

Fig. 11: Scattering parameters of the MSCS obtained with the VNA calibration procedure shown in Fig. 9. Notice in the curves the parameters S11, S22, S21 and S 12.

An important source of error in the MSCS is the input match of the sensor (represented by the parameter S11). It grows from an acceptable reflection coefficient of 0.032 (-30 dB) at 6 MHz reaching a somewhat high value of 0.1 (-20 dB) at about 190 MHz. The reflections, originated in the imperfection of the termination resistors of the coaxial line, perturb the measured current by as much a 10% at 190 MHz. Consequently, for good measurement results, it is important to limit the spectral contents of the input pulses to well below 190 MHz. Fig. 12 show s the normalized power spectrum of the current pulse used to calibrate the sensor. It satisfies this requirement as all spectral components fall below -40 dB of the peak value at about 45 MHz.

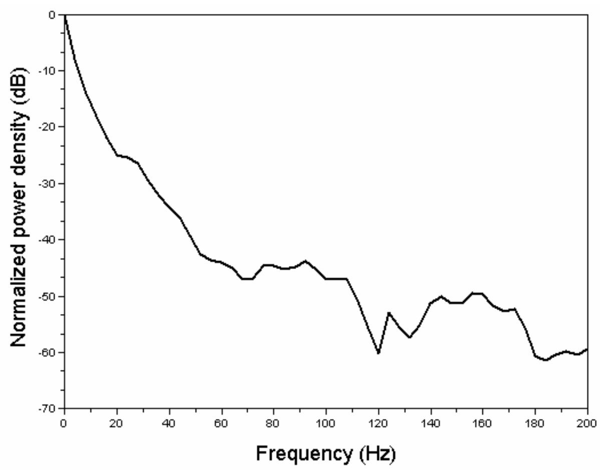

Fig. 12: Normalized power spectrum of the reference current of Fig. 15 obtained with the VNA calibration procedure shown in Fig. 9 dashed line.

2.4.2 Attenuation constant calibration.

The second procedure of calibration uses the setup described in Fig. 13.

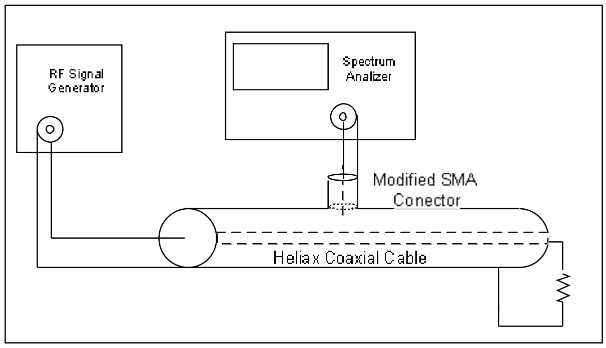

Fig. 13: Experimental setup to obtain the attenuation calibration.

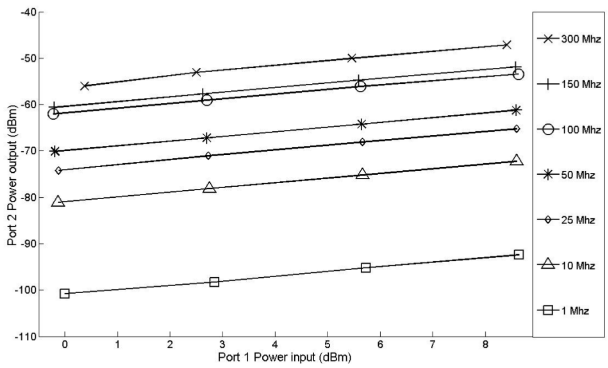

Fig. 14: Calibration curves. Note the linear response in amplitude in each frequency.

The RF signal generator applies a calibrated power signal to the Port 1. The output power signal of the MSCS (Port 2) was measured with a Spectrum Analyzer. Signals of different amplitude and frequency were applied to Port 1. Fig. 14 shows the results of this calibration process: Port 2 has a linear response to the different amplitudes applied to the Port 1. This figure also shows a similar frequency response to the one obtained in the first calibration process. In special note the same 20 dB/decade voltage response that is present in the S21 parameter in Fig 11.

3 RESULTS ANALYSIS.

3.1 MSCS signal processing.

3.1.1 Numerical Integration.

Fig. 15 shows the results obtained in the experimental setup described in 2.3. The current pulse from the FICG, is presented over a time span of 250 ns. The Rogowski coil reference measurement (dashed line) has a rise-time of about 20 ns and a slow decay due to stored energy on the generator. A peak current of 90 A was chosen in order to perform the required calibration of the sensor data.

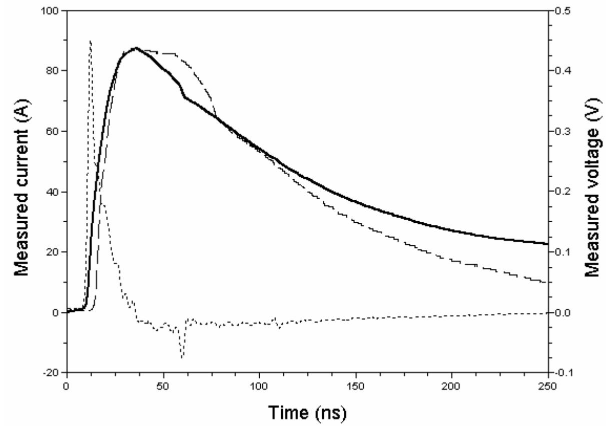

Fig. 15: Measured waveforms on the MSCS. Dashed line: current transformer reference measurement. Dotted line: voltage recorded from the MSCS. Solid line: Calculated current from the measured MSCS voltage. From this relation is possible to obtain the calibration constant *k*.

The measured voltage on the output port of the MSCS, shown as a dotted line on Fig. 15, is a rough representation of the derivative of the reference measurement. Due to the low resolution of the DSOs, two separate measurements at two different vertical scales where performed and the data sets where combined in the final data set. Otherwise, the tail of the pulse would not be adequately reproduced. The downward-pointing peak near 60 ns on the curve is due to a reflection on the non-ideal termination on the DSO side.

To obtain the calculated input current, a simple trapezoidal integration was performed on the numerical data from the MSCS. A scaling or calibration factor was calculated by dividing the peak amplitudes. We got a value of 2.366 A/V. The solid line on Fig. 15 is the waveform of the calculated current on the input of the MSCS after multiplying by the given value.

We got a fairly good reconstruction of the rising pulse. However, the lower the rate of change of the current, the more the curves tend to diverge from each other. This is the expected behaviour because the amplitude of the sensor data is strongly dependent on the derivative of the input current. Slowly varying currents produce low output signals and are more affected by the quantization process.

The reference measurement lags the calculated measurement by an estimated 2.9 ns. This is evidence of a small mismatch in the electrical lengths of the cables used for the current transformer and the MSCS.

3.1.2 Convolutional signal processing.

The improvement of the MSCS signal reconstruction requires a different signal processing methodology. Instead of numerical integration, we apply a convolution in time domain between the four S parameters and the signal registered in the MSCS connector. The procedure is described in [6].

Fig. 16 compares the measured (dashed lines) with the calculated (solid lines) data on a normalized scale. Compared to Fig. 15, the trailing edge of the input current is better reproduced with this methodology.

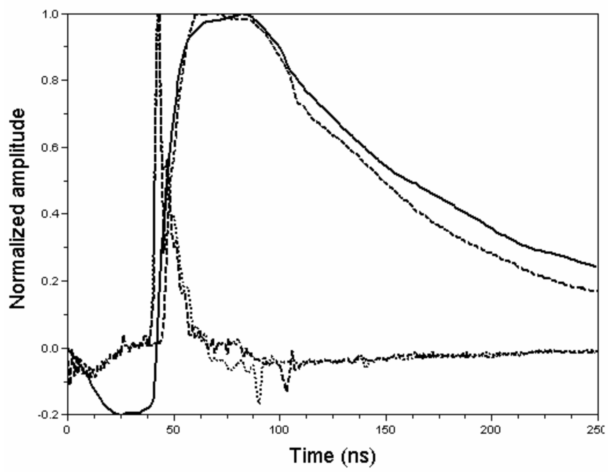

Fig. 16: Normalized response waveforms calculated form the scattering parameters of the MSCS. Dashed lines: reference measurements. Solid lines: Time-shifted calculated responses

3.2 Discussion.

3.2.1 Operation of the MSCS

A qualitative description of the operation of the MSCS can be given as follows. When a forward traveling TEM wave (Fig. 17) propagates on the coaxial cable, a potential difference ΔV is established between the inner and outer conductors of the SMA receptacle. The coupled wave (b2) that constitutes the directly measured signal, is, in theory, proportional to this ΔV

$$b_2 = k\Delta V$$

Where: k is a proportionality constant.

From the telegrapher's equations (1),

$$\begin{aligned}\frac{\partial}{\partial x}V(z,t) &= -L\frac{\partial}{\partial t}I(z,t)\\ \frac{\partial}{\partial x}I(z,t) &= -C\frac{\partial}{\partial t}V(z,t)\end{aligned} \tag{1}$$

Where: L and C are respectively the inductance and capacitance per unit length of the line and V and I are the time-dependent voltage and current along its axis, this ΔV can be approximated as

$$\Delta V \approx -(L\Delta z)\frac{\partial}{\partial t} I(z = z_0, t) \qquad (2)$$

It follows that the measured voltage b_2 is proportional to the time derivative of the current on the coaxial cable. In frequency domain,

$$b_2 = k\Delta V \approx -(kL\Delta z)\, j\mathrm{w}\, I(z = z_0, t)\,. \qquad (3)$$

From equation (3), it is expected that a Bode plot of the transfer function from I to b2 to be a linear function of the frequency (a straight line with a slope of 20 dB per decade). In practice, perturbation of the TEM mode near the insertion point of the SMA receptacle limits the bandwidth of the system.

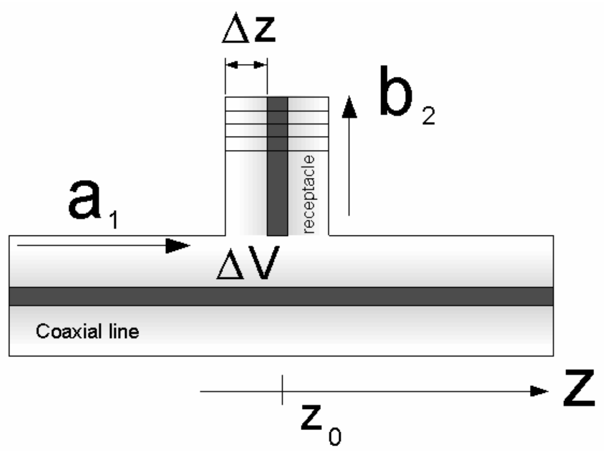

Fig. 17: Internal construction of the MSCS: a1 is the incident wave, b2 is the wave coupled to the MSCS.

3.2.2 Drawbacks of the MSCS

As was explained in the previous section, The MSCS needs a matched termination of the coaxial cable in order to avoid disturbing the sensed current. Of the shelf termination connectors are too sensitive for high current applications, so we had to implement a termination as described on section 2.2.

Termination resistors breakdown voltage and power handling capability are the main limiting factors of the current peak amplitudes that can be measured with this sensor. We found that the used ½W matched termination resistors broke down at near 30 kV, or, equivalently, 600 A.

For a higher current handling capacity, more isolated terminating resistors should be used. However, there is a relationship between the physical size of a component and the associated inductance at high frequencies. Higher inductances on the matched termination results in an increased reflection level (S11 parameter). A compromise must be made between the peak current level and the sensor bandwidth.

3.2.3 Improvements of the MSCS

A matched termination can be entirely avoided if a coaxial line of sufficient length is used instead. Such a line, when terminated in an open or short circuit, would effectively behave as a properly terminated line provided the round-trip delay of the current pulse is greater than its decay time. For example, a 45 m foam dielectric line will accommodate a 300 ns pulse.

Mechanical problems can be avoided if a special kind of coaxial line with a gap in the external conductor is constructed. This instrumentation line can be inserted between the generator and the coaxial transmission line.

3.2.4 Conclusions.

- The MSCS is a sensor appropriated for the measurement of the Roman generator's impulse currents.
- A Scattering matrix technique was applied for the identification and characterization of the MSCS This technique describes the behaviour of the sensor in an acceptable order of accuracy.
- Time convolution is a reconstruction technique adequate for the MCSC signal processing. The time convolution technique is better than the numerical integration process reported in the bibliography.
- The bandwidth of the sensor match with the spectral content of the impulses.
- The installation of the MSCS does not affect the performance of the coaxial cable.

4 ACKNOWLEDGMENT

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5 REFERENCES

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