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CHARACTERISATION OF HIGH VOLTAGE DIVIDERS FOR X-RAY MEASUREMENTS

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Abstract: Invasive high voltage dividers are usually used for the measurements of high voltage x-ray tube and x-ray generators. Because of the diversity of the pulses it is usually difficult to establish a measurement set up for all the waveforms without determining a test procedure for the calibration and characterisation of the measuring system. For example in X-ray diagnostic application, the voltage level is up to 150 kV, the time duration is varying between 50 µs (fast transient overvoltages) to several seconds (temporal overvoltages), the rise time is varying between 10 µs and 500 µs, the waveforms are usually superposed by DC voltage, spikes and a high frequency ripples up to 200 kHz. To overcome these difficulties, LNE (The National laboratory of Metrology in France) and LCOE (the Designated Institute for High Voltage measurements in Spain) have developed, in the frame of 15NRM02 UHV EMPIR European project, a technical procedure to measure with accuracy this large type of pulses using one reference system. An invasive resistive divider (with bandwidth adapted to the measured waveforms) combined with a storage calibrated digitiser is used as a reference standard for the evaluation of the impulse parameters (PPV, Average peaks value, Rise time, duration of the pulse and the fall time). Firstly, high voltage measurements technics have been used to determine the linearity of the reference system for known, traceable and standardised waveforms. Secondary, to ensure a best accuracy while performing the calibration of pulse parameters, we have decided to use a FFT and inverse FFT based technique (deconvolution technics) before the main calibration to correct the frequency non-linearity of the measuring system. The uncertainties of measurements are 0.4 % for Voltage measurements and 2 % for time parameters measurements.

1 INTRODUCTION

High pulsed voltage generators are widely used in the production of X-rays in radiology diagnostics. And big efforts are put into their quality control programmes. The most important set of the x-ray equipment are the reproducibility of the high voltage level and the exposure time according to IEC 60601-1-3 [1]. Because of the diversity of the pulses, it is usually difficult to establish a measurement set up for all the waveforms without determining a test procedure for the calibration and characterisation of the measuring system. For example in X-ray diagnostic application, the voltage level is up 150 kV, the time duration is varying between 50 µs for fast transient overvoltages to several seconds for temporal overvoltages. The rise time is varying between 10 µs and 500 µs, the waveforms are usually superposed by DC voltage, spikes and high frequency ripples up to 200 kHz. The figures 1 and 2 present two examples of High voltage X-ray waveforms.

To overcome these difficulties, LNE (Laboratoire National de Métrologie et d'Essais) and LCOE, (Laboratorio Central Oficial de Electrotecnia) have developed within the frame of 15NRM02 UHV EMPIR European project, a technical procedure to measure with accuracy this large type of pulses using one reference high voltage system.

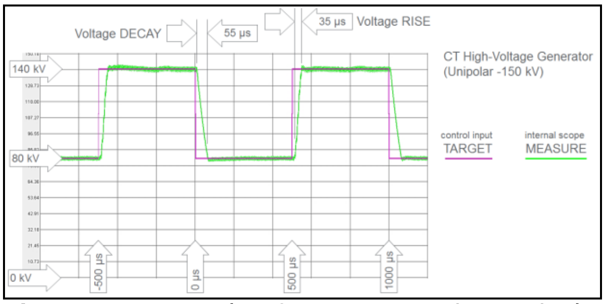

Figure 1: Example of a superposed DC, ripples and impulse waveforms.

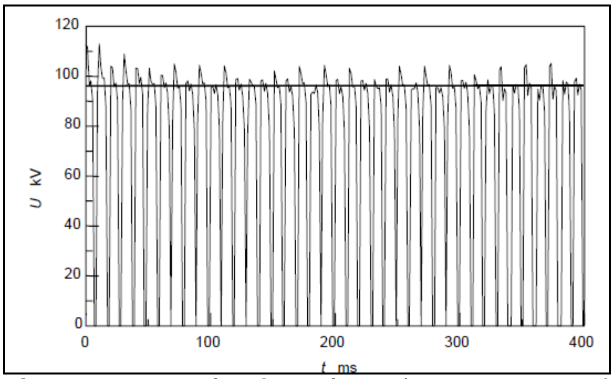

Figure 2: Example of a pulse voltage superposed with irregularities (spikes, overshoots).

2 HV REFERENCE SYSTEM

2.1 DESCRIPTION

The reference system [2], figure 3, is composed by two paired resistive and compensated invasive dividers with 10 MHz bandwidth. The first one is for the anode voltage up to 75 kV and the second one is for cathode voltage down to -75 kV. They are combined with a storage calibrated digitiser with a bandwidth of 100 MHz, 12 bits resolution and 2 GS/s sampling frequency. High voltage measurements technics are used to determine the correction factors of the voltage non-linearity. Software has been developed for signal processing.

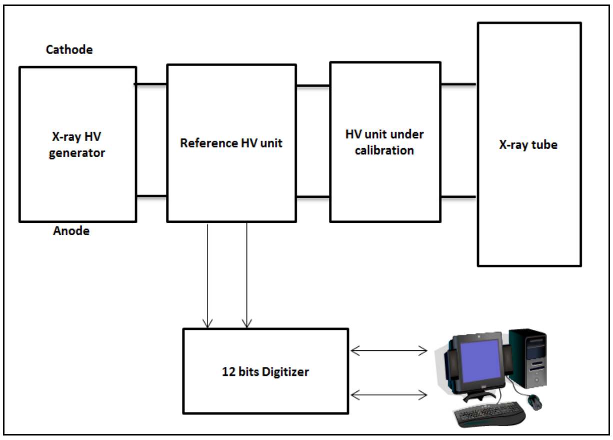

Figure 3: Measurement set up

2.2 THE MEASURED QUANTITIES

The quantity of voltage to be measured is the PPV (Practical Peak Voltage) which is the new quantity adopted by IEC 61676 [3] for the qualification of X-ray machine in radiology diagnostic. The PPV is given by the formulas (1) and (2):

$$PPV = \frac{\int_{Umin}^{Umax} p(U).w(U).U.dU}{\int_{Umin}^{Umax} p(U).w(U).dU} \quad (1)$$

With

$$\int_{Umin}^{Umax} p(U).U.dU = 1 \quad (2)$$

Where p(U) is the distribution function for the voltage U and w(U) is a weighting function. Umax is the highest voltage in the interval, and Umin is the lowest voltage in the interval. The unit of the PPV quantity is the volt (V). The PPV is based on the concept that the radiation generated by a high voltage of any waveform produces the same air kerma contrast behind a specified phantom as a radiation generated by an equivalent constant potential. For a discrete signals it is given by the formula (3).

$$U(PPV)=\frac{\sum_{i=1}^{n} p(U_i).w(U_i).U_i}{\sum_{i=1}^{n} p(Ui).w(U_i)} \quad (3)$$

If, as in most cases, the sampling rate is constant, which means that the samples are taken in equal time intervals, the probability distribution can be set to 1 for all samples, and equation (3) reduces to the simple formula (4):

$$U(PPV)=\frac{\sum_{i=1}^{n}.w(U_i).U_i}{\sum_{i=1}^{n} w(U_i)} \quad (4)$$

When Ui is in units of kV, the weighting function w(Ui) with weighting parameters given in [3].

Other quantities are measured and compared such as the rise time, the pulse width, the peak value, the average peaks and the mean value. All these parameters are easily calculated by the software.

3 HV CHARACTERIZATION

3.1 ROUTINE CHARACTERIZATIONS

Routine characterisations are performed to verify the dividers ability to carry out the measurements without causing significant errors. These errors are essential for the calculation of the uncertainty of measurements. Proximity effects, load impedance effects, temperature effects, frequency effects and the self-heating have been determined.

For the proximity effects, high voltage dividers often have very large input impedances and then limit the power dissipated in the high voltage arm. For example, the dividers used as standard have an input resistor of 300 MΩ in parallel with a capacitor of 10 pF. All the metallic objects around the dividers will create stray capacitance and thus will modify the scale factor. To determine this effect, the scale factor of the divider has been determined by putting a rectangular and an earthed metallic plate from different distances from its axis. The figure 4 presents the obtained result for one of the high voltage dividers. The results show that this effect is important; A distance of at least 60 cm has to be respected for both dividers to reduce this influence down to 0.15 %.

For the load impedance effects: dividers used in radiology diagnostic are usually matched to a storage oscilloscope which has a load impedance of 1 MΩ in parallel with few dozen of pico-farads. This load impedance could influence the scale factor of the divider if it is not calibrated with its associated oscilloscope. In this case this effect is determined by measuring the scale factor for different load impedances. The influence of the standard dividers is found for both dividers to be + 44.10^{-6}.k/pF for capacitive load and

-1,6.10^{-4}.k /kΩ for resistive load (k is the scale factor).

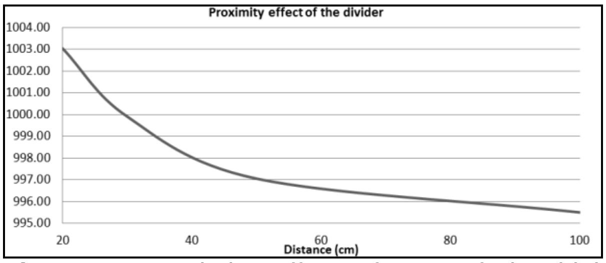

Figure 4: Proximity effect of one of the high voltage divider performed at 30 kV/ 60 Hz.

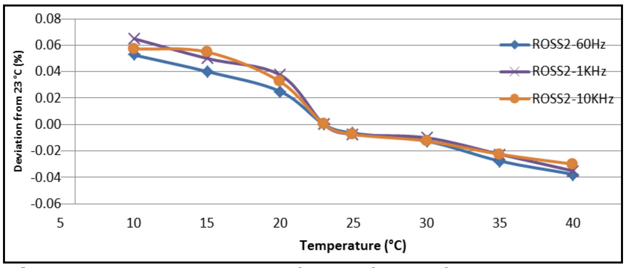

Figure 5: Temperature dependence from 23 °C.

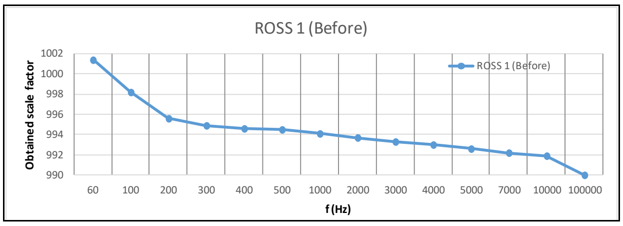

Figure 6: Frequency linearity up to 100 kHz

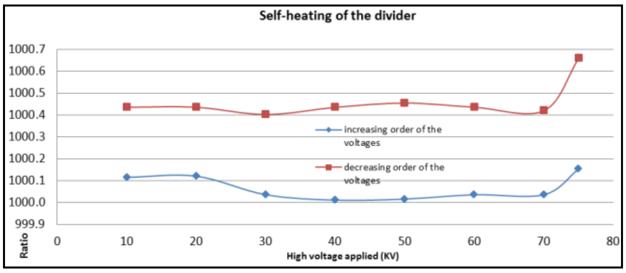

Figure 7: Self heating of the divider.

For the temperature effects: in-situ measurements involve temperature corrections because the operating temperature is different from that used for the calibration which is in our case equal to (23 ± 1) °C. Temperature dependence has been determined at 1000 V at frequencies of 60 Hz, 1 kHz and 10 kHz as shown in figure 5. The relative deviation from 23 °C is less than 0.1 % for both dividers. The influence of temperature could be neglected for a range of [10-40] °C.

For the influence of frequency, the voltage pulses undertaken in this study could include signals with high frequency components. The frequency linearity has been determined by measuring the scale factor at low voltage (1000 V) for frequencies up to 100 kHz. The load impedance was a resistor of (1,0022 ± 0,0010) MΩ in parallel with a capacitance of 14 pF. The results are presented in figure 6. The scale factor at DC voltage for a load of (1,0000 ± 0.0010) MΩ was 1000,1. We see that the divider is not linear; the relative change against frequency from DC to 100 kHz is about 1 % especially observed at low frequencies (DC to 300 Hz). This error could have an impact on time parameters of larges pulses which are usually contain major low frequency components.

For the self-heating of the divider, this effect is usually determined, for restive dividers, at DC voltage by increasing the voltages from 0 V to the nominal voltage, by applying the nominal voltage for a large time (for example 30 minutes to one hour) and after that by decreasing the voltage to 0 V. The scale factor is measured during the increasing and the decreasing of the voltage. The difference between the two series of measurements gives good estimator of the self-heating effect. The results obtained by this method are shown in the figure 7, both dividers have similar characteristics. The self-heating is less than 0.05 %.

3.2 HIGH VOLTAGE LINEARITY

High voltage technics described in IEC 60060-1&2, [4] and [5], were used to determine the linearity of the reference measuring systems for known, traceable and standardised waveforms. The reference measuring system was calibrated for lightning impulses (1.2/50 µs), switching impulses (250/2500 µs), chopped impulses, rectangular impulses, AC voltage and DC voltages. Every calibration was performed by comparison to a high voltage reference system traceable to SI. For example, the figure 8 presents the calibration procedure for lightning impulse, switching impulse and rectangular impulse measurements.

The lightning impulse calibration was carried out at eleven voltage levels up to 120 kV (20 kV, 30 kV, 40 kV, 50 kV, 60 kV, 70 kV, 80 kV, 90 kV, 100 kV, 120 kV) applying ten repetitions for each voltage level.

The switching impulse calibration was carried out at six voltage levels up to 75 kV (10 kV, 20 kV, 30 kV, 40 kV, 50 kV, 75 kV), ten impulses for each level and for each polarity (positive and negative). Two different full switching impulse waveforms were applied:

- T_{1A}: 134/2760 µs
- T_{1B}: 70/2760 µs

Furthermore, the switching chopped impulse technic was used to generate rectangular pulses with duration up to 10 ms. The calibration was performed at 70 kV level with discrete duration (Δt) of 0.2 ms; 1 ms; 10 ms. Taking into account that switching impulses have a double exponential waveform, a slow decreasing after the peak voltage is produced (Figure 10). DC chopped impulse technic was used to generate rectangular pulses with duration up to 2 s. The calibration was also performed at 70 kV level with discrete durations (Δt) of 100 ms; 500 ms; 1 s; 2 s as it is shown in figure 10.

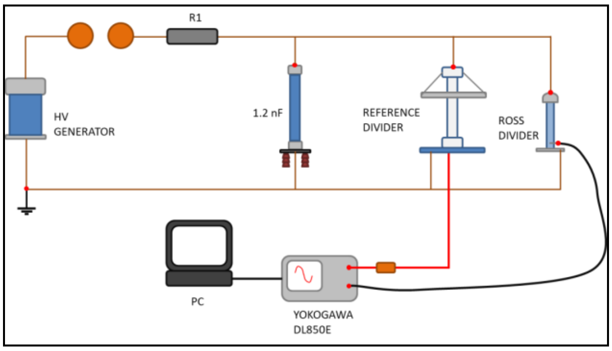

Figure 8: Calibration set up at LCOE for lightning impulse, switching impulse and rectangular impulse measurements. The resistor R1 was selected to obtain the desire waveforms.

Figure 9: Circuit arrangement at LCOE.

The results of high voltage characterisation are summarized in the table 1. Their associated uncertainties are given in table 2. The table 3 summarizes the linearity of the divider versus the voltage from the lowest to the highest voltage to the maximum voltage. Comparable results were found for two dividers with the same brand and type. It is shown in table 1 that for DC chopped impulses or switching impulses (impulse duration ≥ 1 ms) the divider reaches its ratios for DC and AC voltages.

4 IN-SITU CALIBRATION PROCEDURE

4.1 TEHCNICAL PROCEDURE

From the results of characterisation we have decided to implement a calibration procedure, figure 11. It could be probability valid for the calibration of a large high voltage x-ray units available in the market (Dynalyser IIIU from Radcal manufacturing, GiCi-PMI Model H1049 from bleeder manufacturing, etc.).

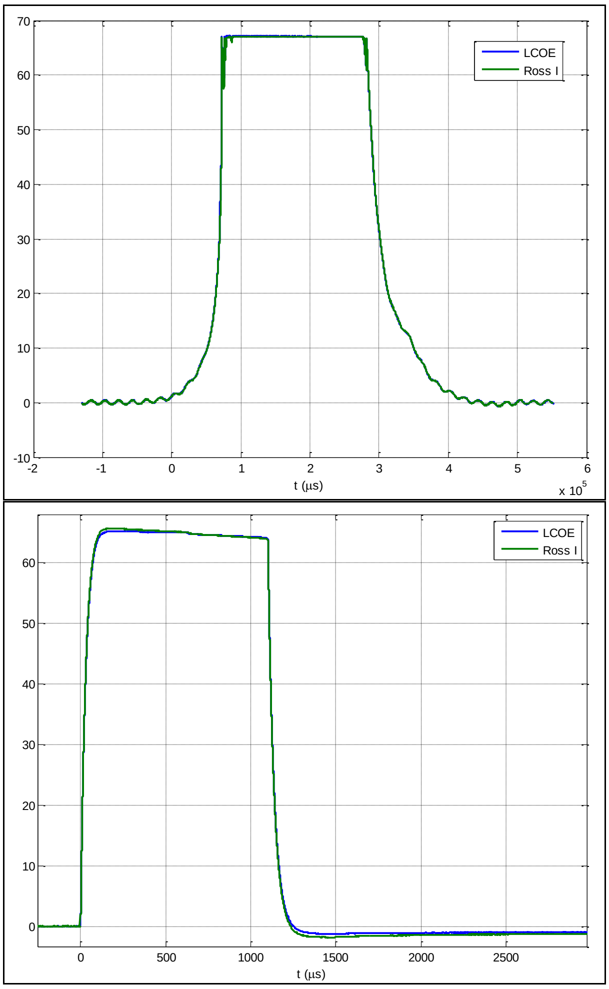

Figure 10: Example of SI chopped impulse (1 ms). (b) and DC chopped impulse (200 µs).

Table 1: Results of the high voltage characterisation.

Waveform type:	Scale factor	Error for time parameters	
		Front time	Duration
DC voltage, 70 kV	999,97		
AC voltage (50 Hz), 50 kV	998,1		
Lightning impulse 1 ,2 /50 µs, 70 kV	995,0	-0,2 %	0,1 %
Switching impulse 70 /2760 µs, 70 kV	992	-0,9 %	-3,0 %
Switching impulse 134 /2760 µs, 70 kV	992	-0,1 %	-3,2 %
Switching chopped at 0,2 ms, 70 kV	995		
Switching chopped at 1 ms, 70 kV	998		
DC chopped at 100 ms 70 kV	999		
DC chopped up to 2 s, 70 kV	999		

Table 2: Uncertainty of measurement.

Waveform type:	Scale factor	Front time	Duration
DC voltage	0,021 %		
AC voltage	0,10 %		
Lightening impulse 1 ,2 /50 µs	0,63 %	2 %	1 %
Switching impulse 70 /2760 µs	0,45 %	2 %	1 %
Switching impulse 134 /2760 µs	0,45 %	2 %	1 %
Switching and DC chopped	0,2 %		

Table 3: Linearity of the divider from 10 kV to the maximum voltage.

Waveform type:	Scale factor	Front time	Duration
DC voltage	0,03 %		
AC voltage	0,10 %		
Lightening impulse 1 ,2 /50 µs	0,10 %	0,4 %	0,4 %
Switching impulse 70 /2760 µs	0,20 %	1,2 %	0,5 %
Switching impulse 134 /2760 µs	0,30 %	1,6 %	0,7 %

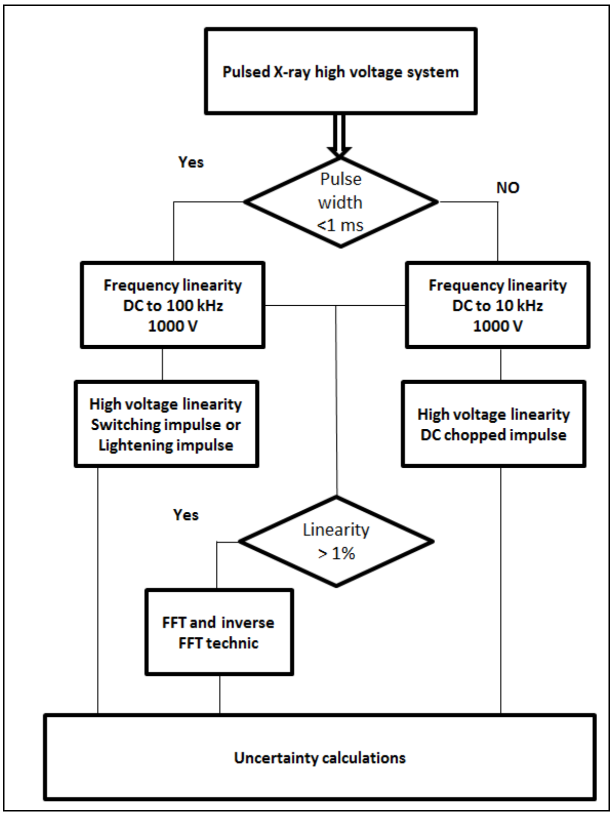

Figure 11: Procedure for the calibration of x-ray systems.

For waveforms with pulsed width highest than 1 ms, the frequency linearity could be measured at low voltage for example at 1000 V from DC to 10 kHz. The maximum deviation of the scale factors against frequency is kept for uncertainty calculation. The linearity against voltage could be done at DC chopped impulse or at DC voltage for large pulses.

For waveforms with pulse width from 50 µs to 1 ms, the linearity frequency could be performed from DC to 100 kHz. The linearity against voltage could be done at switching impulse (for example 20/1000 µs, 250/ 4000 µs) or at lightening impulse for very fast pulses. Linearity at DC chopped impulse at 0.2 ms could also be checked.

For the measurements of time parameter, the linearity against high voltage is difficult to establish because they are usually correlated with the uncertainty of the voltage. Relationships could be identified by experience between the uncertainty of the voltage and its impact on the uncertainty of the rise time and the duration of the pulse. For example, coefficients of 4 and 1 have been identified respectively for the rise time and the duration of the pulse at level of 50 % for rectangular impulses. This coefficient could be calculated easily by experience (Measure the exact voltage and the exact times parameters, recalculate the time parameters for a 101 % of voltage. The obtained difference is the error involved by 1 % of voltage uncertainty.

Time parameters are also affected by the frequency non linearity. At low frequency it produces errors for the measurement of the duration of the pulse. At high frequency it affects the rise time. When the frequency non linearity is higher than 1 %. A FFT and inverse FFT technic could be used (chapter 4).

4.2 UNCERTAINTY CALCULATION

The uncertainties of measurement are calculated according to the GUM [6] within the contributions coming from the reference high voltage dividers, the digitizer and the software. The tables 4, 5 and 6 present respectively the uncertainty budget for the voltage, the rise time and the duration of the pulse. All the contributions are coming from the results of characterization.

Table 4: Uncertainty budget for the voltage

Uncertainty sources	Contribution (k=1)
Frequency linearity	1 % ÷ 2√3
Influence of temperature	0,04 % ÷ 2√3
Self-Heating	0,1 % ÷ 2√3
Rise time of the digitizer	0,01 % ÷ 2√3
Calibration at low voltage	0,2 % ÷ 2
Calibration of digitizer	0,2 % ÷ 2
Influence of software	0,03 % ÷ 1
Uncertainty for the voltage (k=2)	0,64 %

Table 5: Uncertainty budget for the rise time

Uncertainty sources	Contribution (k=1)
Influence of the uncertainty of the voltage	4×0,64 % ÷ 2
Dividers linearity	1,6 % ÷ 2√3
Maximum observed error	0,9 % ÷ 2√3
Determination of particular points (times at 10 % and 90 %)	0,15 % ÷ 2√3
Influence of the digitizer	0,0 %
Uncertainty for the rise time (k=2)	3 %

Table 6: Uncertainty budget for the duration.

Uncertainty sources	Contribution (k=1)
Influence of the uncertainty of the voltage	1 ×0,64 % ÷ 2
Dividers linearity	0,7 % ÷ 2√3
Maximum observed error	3,1 % ÷ 2√3
Determination of particular points (times at 50 % or at 90 %)	0,15 % ÷ 2√3
Influence of the digitizer	0,0 %
Uncertainty for the duration (k=2)	2,0 %

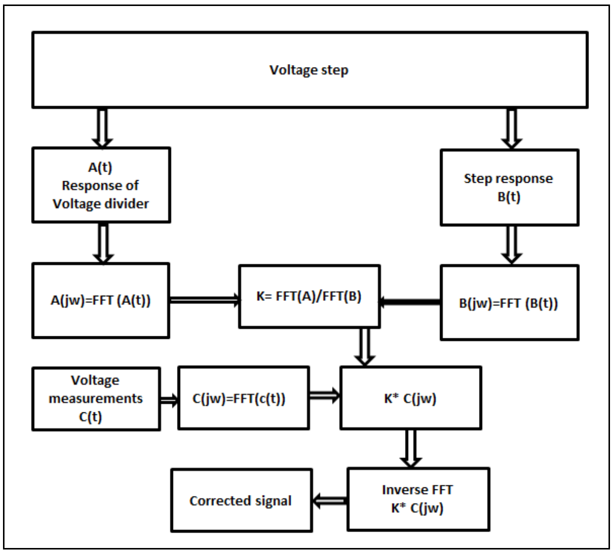

Figure 12: FFT and Inverse FFT technique

4.3 FFT AND INVERSE FFT BASED TECHNIC

In order to enhance the uncertainty of measurements for non-ideal high voltage dividers presenting very high frequency non linearity , a FFT and an inverse FFT based method, [7], figure 12, could be used to correct this non-linearity. An ideal step voltage is injected to the HV divider. The step response of the clamp meter (or dividers) is measured by using its digitizer in order to minimize its effect to the result. Both FFT of the input and output steps are calculated (after being improved by some signal processing for a best FFT calculation; Sweeping, balancing, zero-padding, normalization, filtering) to determine the errors for each frequency component. During the measurements the same signal processing is performed, the correction is applied to obtain the corrected signal in time domain. The frequency non linearity could be reduced by this technic down to 0,5 %. The uncertainty of measurement are then imporved, in our case, to 0,4 % for the voltage, 2 % for the rise time and 1 % for the duration of the pulse.

5 CONCLUSION

Reference system for the calibration of pulsed X-ray high voltage tube has been developed. Available and traceable high voltage technics according to IEC 60060-1&2 have been used to characterize the reference system for in-situ measurements. The evaluation of the uncertainty of measurements has been discussed. A technical procedure has been proposed to simplify the characterization of X-ray high voltage units. This procedure includes a FFT and inverse FFT technic to be used to correct the frequency non linearity of the high voltage measuring unit.

ACKNOWLEDGMENTS

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