Calibration of LCL-Probes

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1 Introduction

The standard CISPR 22 suggests a method of using ISN (Impedance Stabilisation Networks) to measure the common mode disturbances on unshielded symmetrical transmission lines. Depending on the degree of unbalance about earth of the nominally symmetrical line, a conversion from symmetrical signals to (unwanted) asymmetrical or common mode signals is caused. The LCL (Longitudinal Conversion Loss) describes this unwanted conversion of signals. The definition of LCL is given in [1] and [2].

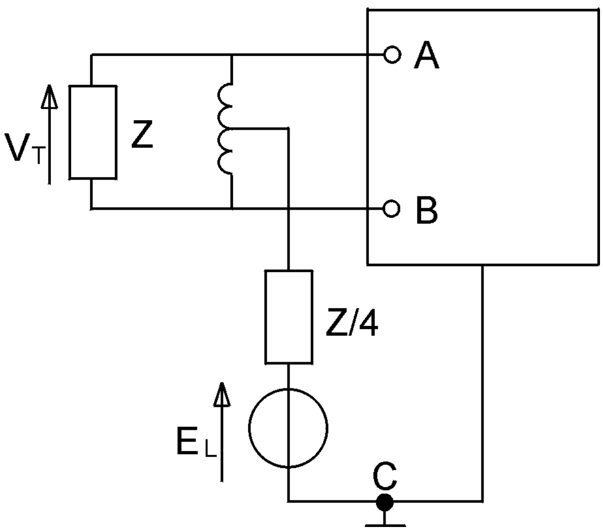

Figure 1: Definition of the LCL-measurement according to ITU-T

The LCL is the ratio of the longitudinal voltage E_L and the transverse voltage V_T. Within this document the logarithmic LCL is preferred in most cases:

$$LCL = 20log_{10}\left|\frac{E_L}{V_T}\right| dB$$

The characteristic impedance Z is assumed to be 100 Ω unless otherwise stated. Since several experts encountered big deviations in measurement results of LCL, a meeting was initiated by the German government body RegTP to find out the reasons for the unacceptable large deviations in measured LCL-values. The two days meeting was held in Kolberg at the RegTP laboratory [6]. The main aim of the meeting was to find the reasons for the large deviations and to propose a method which complies with the definition in [1]. A further aim was to define networks, which can be used for the calibration of LCL-probes. These networks should have calculable characteristics in order to compare measured and theoretical LCL-values. A method to construct a LCL-probe was described in [3]. Based on this paper a LCL-probe was constructed by the author and compared to a probe suggested in [4], which has been used by several manufacturers of ISN.

2 Networks with defined unbalance for the calibration of LCL-probes

There are many possibilities to compose networks for calibration purposes. For the calibration of LCL-probes several criteria should be fulfilled:

- Calculable characteristics
- High precision and stability
- Realistic impedance characteristics (common and differential mode impedance)
- Frequency independant characteristics
- Two different methods to assess the characteristics of the networks to provide

traceability to basic quantities (e.g. dc-resistance or rf-attenuation)

A very simple approach to achieve a defined unbalance is to use two resistors as depicted in Fig. 2. This circuit is furthermore called L-circuit within this document. The symmetrical terminals are assigned with "A" and "B", the reference ground is "C". According to [3]

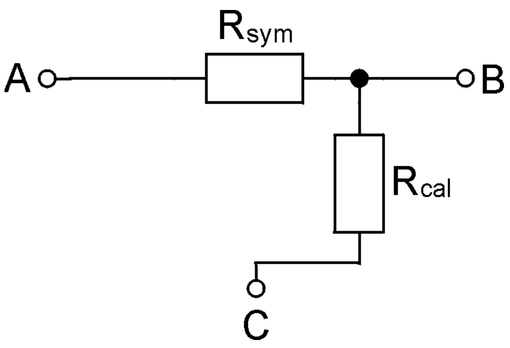

Figure 2: L-Circuit

the LCL can be calculated using the following equation with $Z = 100\,\Omega$:

$$LCL_L = 20log_{10} \left| \frac{[R_{sym}||Z] + 4R_{cal} + Z}{2 \cdot [R_{sym}||Z]} \right| dB$$

The L-circuit has some disadvantages, the major one is the common mode impedance, which strongly depends on the provided LCL-value. The higher the LCL, the higher the common mode impedance of the L-circuit. However, the symmetrical impedance is constant for all LCL-values, since it depends only on the Resistor R_{sym}. The common mode impedance is always equal to R_{cal}. At higher LCL-values the common mode impedance rises to many $k\Omega$, in this case internal stray capacities of the probe will deteriorate the calibration accuracy, especially at higher frequencies, typically above 10 MHz.
Therefore the L-circuit should only be regarded as a rough estimation tool for evaluating the performance of LCL-probes. The Fig. 3 shows the LCL-value versa R_{cal}, which is equal to

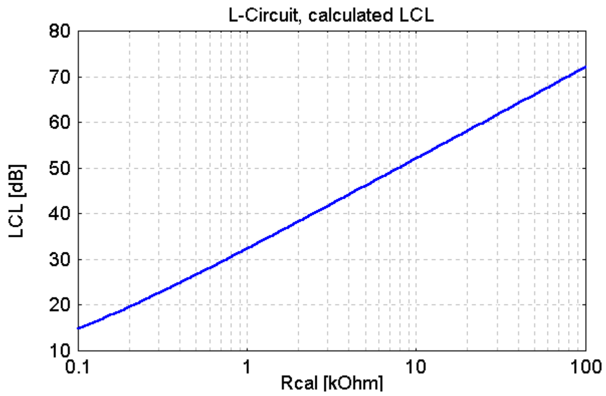

Figure 3: L-Circuit, LCL versa R_{cal}

the common mode impedance of the L-circuit.

A much better network to provide a defined unbalance is the T-circuit as depicted in Fig. 4. It consists of three resistors R_A, R_B and R_C.

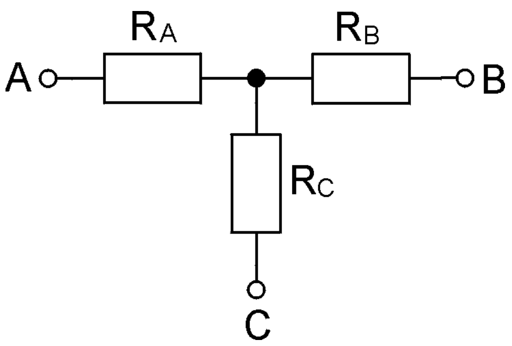

Figure 4: T-Circuit

The T-circuit provides both, a defined symmetrical (differential mode) and a defined asymmetrical (common mode) impedance. It is always possible to find a combination of resistors, fulfilling all conditions for the differential mode, the common mode and the desired LCL-value. Referring again to [3] the LCL can be calculated using the following equation:

$$LCL_T = 20log_{10} \left| \frac{2Z + 4R_C}{|R_B - R_A|} - \frac{|R_B - R_A|}{2Z} \right|$$

In order to obtain a good accuracy for the calibration of LCL-probes, the T-circuit should be designed in a way, that $Z_{sym} = 100\,\Omega$ and $Z_{asym} = 150\,\Omega$ is achieved, which are the recommended nominal impedances in [5] for ISN. Z_{sym} is the symmetrical impedance at the terminals "A" and "B" of the reference circuit, Z_{asym} is the impedance between the shorted terminals "A" and "B" to the reference ground "C". Some calculated values for the resistors R_A, R_B and R_C and corresponding LCL_T are given in the tabular Tab. 1. Especially for high LCL-values the differences of the resistors R_A and R_B are very small, this indicates the need for highly accurate determination of the resistance in order to have a good agreement between calculated and measured results. During the experiments the resistance values have been determined using a highly accurate Leeds and Northrup percent bridge. A practical problem may arise due to transition resistances when connecting the T-circuit for e.g. 80 dB LCL to the resistive bridge. The corresponding values of R_A and R_B are $49.97\,\Omega$ and $50.03\,\Omega$ respectively, a difference of $0.06\,\Omega$ only! Contact repeatability must be very accurate to avoid an unwanted influence on the balance at such high LCL-values.

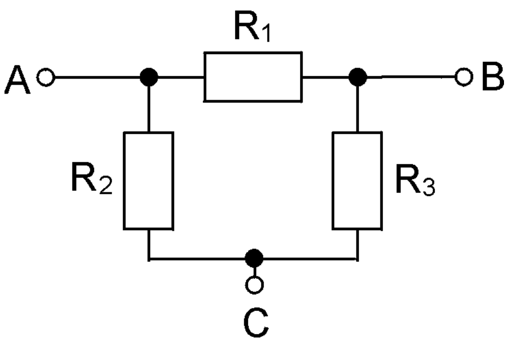

Figure 5: π-Circuit

A workaround to reduce the contacting uncertainty is to transform the T-circuit into a terminal-equivalent π-circuit as given in Fig. 5. The π-circuit (also called triangle or delta-circuit) is composed of three resistors R_1, R_2 and R_3. The following equations show how to transform the resistors from one circuit to the other and vice versa.

$$R_1 = R_A + R_B + \frac{R_A R_B}{R_C}$$

$$R_2 = R_A + R_C + \frac{R_A R_C}{R_B}$$

$$R_3 = R_B + R_C + \frac{R_B R_C}{R_A}$$

$$R_A = \frac{R_1 R_2}{R_1 + R_2 + R_3}$$

$$R_B = \frac{R_1 R_3}{R_1 + R_2 + R_3}$$

$$R_C = \frac{R_2 R_3}{R_1 + R_2 + R_3}$$

Applying this transform we get approx. 6 times larger resistance values for the resistors R_2 and R_3 being in charge to control the balance (or unbalance) of the circuit. It is obvious that contact uncertainties do not have such a strong influence on the delta-circuit. In the above case of 80 dB LCL we obtain $299.79\,\Omega$ and $300.21\,\Omega$ for R_2 and R_3, resulting in a difference of $0.42\,\Omega$, which is much better to reproduce in practical applications. Some calculated LCL-reference circuit values are given in Tab. 1 and Tab. 2.

3 Experimental Results

Both L- and π-circuits have been realized and evaluated for LCL-values of 30 dB to 60 dB respectively 70 dB.

The experimental results are in good agreement with theory. The resistors have been tuned on the resistive Percent-Bridge with a typical uncertainty of 0.01 % according to

T-circuit ,$Z_{sym} = 100\Omega, Z_{asym} = 150\Omega$			
LCL_T	R_A	R_B	R_C
$[dB]$	Ω	Ω	Ω
20	13.70	86.30	138.18
25	30.10	69.90	128.96
30	38.90	61.10	126.21
35	43.77	56.23	125.38
40	46.50	53.50	125.12
45	48.03	51.97	125.04
50	48.89	51.11	125.01
55	49.38	50.62	125.00
60	49.65	50.35	125.00
65	49.80	50.20	125.00
70	49.89	50.11	125.00
75	49.94	50.06	125.00
80	49.97	50.03	125.00

Table 1: Calculated resistor values for the T-Circuit

π-circuit, $Z_{sym} = 100\Omega, Z_{asym} = 150\Omega$			
LCL_π	R_1	R_2	R_3
$[dB]$	Ω	Ω	Ω
20	108.56	173.82	1094.92
25	116.32	214.59	498.34
30	118.83	245.46	385.55
35	119.63	266.75	342.68
40	119.88	280.37	322.58
45	119.96	288.64	312.29
50	119.99	293.50	306.78
55	120.00	296.30	303.77
60	120.00	297.91	302.11
65	120.00	298.82	301.19
70	120.00	299.34	300.66
75	120.00	299.63	300.38
80	120.00	299.79	300.21

Table 2: Calculated resistor values for the π-Circuit

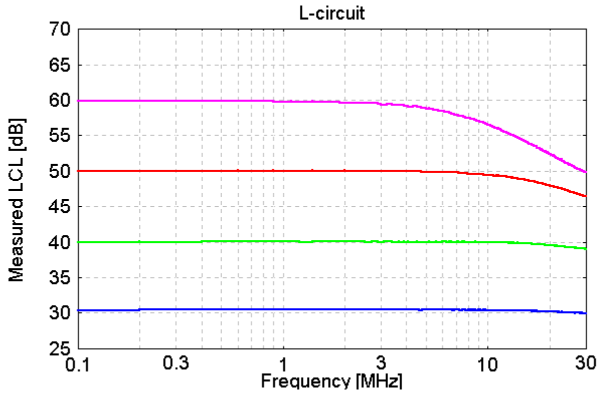

Figure 6: Measured LCL (L-Circuit)

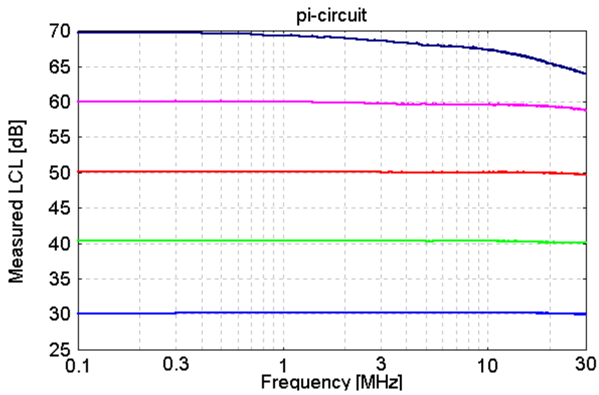

Figure 7: Measured LCL (π-Circuit)

Tab.1 and Tab.2. Afterwards the LCL was measured using a Network Analyzer and the LCL-probe PB 44. The self-LCL of the PB 44-probe was 69 dB at 30 MHz, 84 dB at 10 MHz and better than 90 dB in the range from 100 kHz to 5 MHz. In the frequency range up to 1 MHz it was possible to predict the measured LCL with an uncertainty of less than 0.5 dB, even for LCL-values up to 60 dB. The experimental results for the L-circuit is presented in Fig. 6, the results for the π-circuit in Fig. 7. Especially for higher frequencies and high LCL-values the advantages of the π-circuit as a reference network for LCL-probe calibration are obvious. A comparison at 30 MHz and a nominal LCL-value of 60 dB at low frequencies shows a frequency response of approx. 1.2 dB for the π-circuit, the L-circuit has a frequency response of approx. 10 dB instead! The π-circuit fulfills the requirement of $Z_{asym} = 150\,\Omega$ and also $Z_{sym} = 100\,\Omega$, in contrast to the L-circuit, which offers a $Z_{asym} \approx 24\,k\Omega$. The high common mode impedance of the L-circuit is the reason, why probe imperfections caused by unavoidable parasitic shunting capacities contribute much more to the L-circuit than to the T- or π-circuit. Therefore the T- or π-circuits should be the preferred choice for probe calibration at higher LCL-values (above $\approx$ 35 dB) and frequencies (above $\approx$ 10 MHz). Furthermore they represent impedance characteristics, which come very close to the nominal impedances of ISN according to [5]. The advantages of the L-circuits are the simple structure and uncritical practical realisation, but their application is limited to moderate LCL-values (below $\approx$ 35 dB) and frequencies (below $\approx$ 10 MHz).

4 Calibration Uncertainty

The measurement uncertainty for LCL-probe calibration itself depends on various parameters, which can be mainly divided into the following categories:

- Uncertainty of the Network-Analyzer or Generator-Receiver combination
- Uncertainty caused by LCL-probe imperfections
- Uncertainty caused by reference circuit imperfections
- Uncertainty caused by the measurement of the resistor values

In this document the Network Analyzer error contribution will be assumed to be negligible, bearing in mind that this won't apply in real life. Examples for the probe imperfections are: Capacitive unbalance inside the probe, resulting in a detoriation of the probe's inherent self-LCL. A sufficient self-LCL of the probe is essential to improve the calibration accuracy. The lumped capacities inside the probe should be in the order of 0.01 pF or less to ensure a good self-LCL. A direct measurement of such small capacity differences is not possible of course, therefore the self-LCL is optimized for the highest operating frequency of the probe using a perfectly balanced 100 Ω symmetrical load. LCL-probes for the operating range 100 kHz to 30 MHz can reach a self-LCL of up to 70 dB at 30 MHz. The following error estimations depending on the probe's self-LCL have been derived from measurements: With a self-LCL margin of 20 dB or more the error for the LCL to be measured was less than +0 dB / - 0.5 dB. With a self-LCL of the probe which is 10 dB higher than the LCL to be measured the error was +0 dB / -1 dB approximately. A drastical rise of the measurement error appears in cases where the self-LCL margin is e.g. 5 dB only. Therefore the minimum requirement for the probe's self-LCL should be at least 10 dB higher than the maximum LCL value to be measured at the respective frequency.

Reference circuit imperfections are mainly caused by impedance deviations and capacitive unbalance. The capacitive unbalance can be investigated if the symmetrical terminals "A" and "B" of the reference circuit are inverted. With a perfectly balanced probe and reference circuit the measured LCL is exactly the same. In practical realisations there will always be either a reduction or an addition of the unbalance of each network (unbalance compensation). Probes and reference circuits for probe calibration should provide the possibility to invert the terminals in order to estimate the quality of the measurement results. Typical error contributions when inverting the terminals of the reference circuit have been $\pm$ 0.5 dB.

The measurement of the resistor-values is uncritical for the L-network, which should preferrably be applied at LCL-values below 35 dB. For higher frequencies the T-circuit or π-circuit are a better choice because of their stable common mode and differential mode impedance. During the experiments the π-circuit was found to be the circuit with the most accurate characteristics. The influence of resistive measurement errors have been reduced to 0.01 % of the resistor value. The uncertainty caused by resistor measurements errors depends strongly on the LCL-value. The higher the LCL, the higher the influence of the resistor measurement uncertainty.

The total measurement uncertainty for LCL-probe calibration can be assumed to be +0.5 dB / -1.5 dB, if the LCL-value is between 25 dB and 65 dB and the probe provides a self-LCL-margin of at least 10 dB or more than the LCL-value to be measured.

It should be pointed out that the LCL-probe calibration uncertainty is not the uncertainty for LCL-calibration of ISN. Generally the calibration of the probe will be more accurate than the calibration of ISN. Especially in cases where the ISN do not provide a dedicated reference ground terminal (e.g. with the popular RJ 45 connector), the influence of the capacitive unbalance to the environment and the (normally increased) common mode impedance will contribute to a total measurement uncertainty of $\geq \pm 3$ dB for high LCL-values and frequencies. In cases where the reference ground terminal is not accessible, a connection with low inductance and minimum length (e.g. copper strip) must be provided between probe and ISN housing. The nominal common mode impedance of $Z_{asym} = 150\,\Omega$ may also be influenced by the height of the common mode conductor above ground. A further influence on the common mode impedance of the ISN is caused by the used cable category adjustment networks. The lower the LCL, the higher the shunting effect of the cable category adjuster. For LCL-values from 25 dB up to approx. 35 dB the asymmetrical (common mode) impedance may be less than the lower limit, specified in [5]. Therefore the common mode impedance of an ISN should be determined only without cable category adjusters. If the ISN common mode impedance is within the specified margin of $150\ \Omega \pm 20\,\Omega$, the influence on the LCL will be around ± 1 dB.

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