Characterization of a Modified LISN for Effective Separated Measurements of Common Mode and Differential Mode EMI Noise

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Abstract -- **The compliance with standards calls for proper designed EMI filters. EMI typically comprises common mode (cm) and differential mode (dm) noise. A systematic optimization of EMI filters requires the knowledge of the contribution and distribution of these two noise sources. The paper discusses different methods that allow the independent measurement of cm and dm noise. One suitable method described in detail integrates the separation set-up into the Line Impedance Stabilization Network (LISN). However, a correct interpretation of the measured results requires a characterization of the unavoidable modal conversion of the complete set-up – i.e. the measured level at the dm output in case of pure cm excitation and vice versa. As shown in this paper, the implementation of a standard LISN introduces a high amount of imperfections causing the undesired modal conversion. Thus, for the first time, this paper describes the characterization of the whole set-up including the LISN.**

Index Terms-- **Common mode (cm), characterization of noise separation, differential mode (dm), EMC, EMI, LISN, noise separation.**

I. Introduction

Electromagnetic interference (EMI) emission causes great concern among system designers. With respect to conducted emissions, filters are needed in order to fulfil the limits given by legislation. However, for being able to design a filter systematically, the designer has to have knowledge of the exact distribution between common mode (cm) and differential mode (dm) noise since the filter techniques for the two noise disturbances are completely different. Hence, it is imperative to measure them separately in order to design a suitable filter based on the obtained data.

Different cm and dm separation techniques have already been reported in [1-4]. However, all of them exhibit drawbacks. In addition, they are used in combination with a standard line impedance stabilization network (LISN), but none of the hardware based ones are characterized in combination with the standard LISN, thus the influence of the imperfect LISN is neglected within these approaches. However, as it is shown in this article, the LISN has a great impact on cm to dm and dm to cm rejection. Therefore, the characterization has to be done taking the LISN into account due to the fact that regular EMI compliance measurements have to be done with the standard LISN.

In this paper, a very effective method for the separation of conducted cm and dm EMI noise emissions, which has already been used for several years at our place, is described. Despite the very high obtained rejection values, the necessary equipment for this separation technique consists of just two current probes that can be easily added to a standard LISN. This set-up has already been used in a comparative study of industrial switch mode power supplies [5]. To the authors' knowledge the paper describes for the first time the detailed characterization and discussion of the measurement set-up in combination with the LISN. The investigations are carried out in the frequency range from 150kHz to 30MHz defined for conducted interference by international standards.

II. Various Separation Techniques

There are several separation techniques that can be categorized in three main groups: Software based separation, separation with current probes and separation with an additional network (Paul-Hardin or power combiner).

A partial software based separation technique can be found in [4] and [6]. Measurements discussed in these papers were done with a differential mode rejection network or a general noise separator and without. One noise part (cm or dm) was obtained immediately and the other one was calculated from the data obtained. Since a hardware noise separator is needed, there is no advantage in using this method. In addition, no investigation on cm or dm noise rejection was published. Software separation methods based on time domain

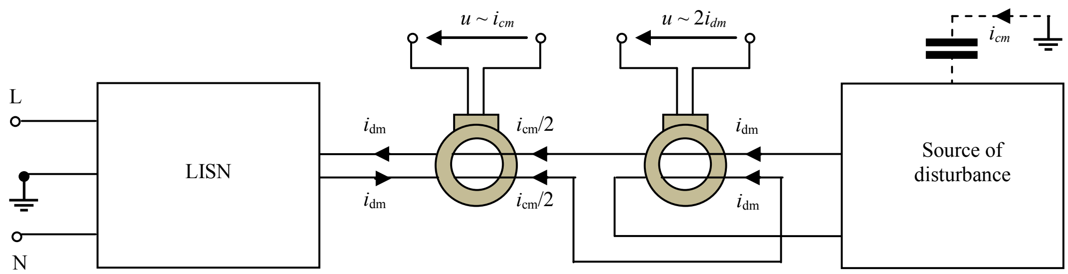

Fig. 1: Separation of cm and dm current by using a current transducer or probe

measurements [7] face the problem that the phase needs to be measured very accurately, or the resulting calculation may be very inaccurate. Furthermore, the A/D converters in oscilloscopes are usually limited to around 8bit. Hence, the provided dynamic range is poor.

The second method relies on current probes between the LISN and the source of disturbance [1-8], as seen in Fig. 1. There are mainly two problems involved with this method. First of all, both current probes are exposed to the typically high supply current. Therefore saturation or sensitivity problems will arise. In addition, the line impedance inside the LISN is frequency dependant and therefore a frequency dependant conversion factor has to be taken into account in order to obtain the desired cm and dm voltage.

Another possibility to separate the cm and dm noise is based on a network proposed by Paul and Hardin [3,9]. The device is placed at the LISN outputs and provides matched impedance. One problem that may arise is the fact that it is rather difficult to realize the high quality ground free transformers as discussed in [10]. The characterization of the cm and dm rejection using the Paul-Hardin network resulted in approximately 50 dB, but the standard LISN was not taken into account. This appears to be a reasonable value. However, other methods result in the same or an even better rejection as will be shown in this paper. In addition, the LISN plays a major role in the EMI measurement and especially in the cm and dm rejection as it is explained in the next paragraph. Therefore it is very important to characterize the cm and dm splitting devices with the LISN and not without.

The separation of cm and dm noise with power combiners [2,8,9] is similar to the last method. The signals from the LISN are fed into either a 0° power combiner (shown in Fig. 2) or a 180° power combiner (shown in Fig. 3) in order to obtain the cm or the dm noise voltage. As shown in [2] a cm and dm noise rejection of at least 50dB for the frequency range of 10kHz to 30MHz is achievable. Again, the characterization was done without the LISN and a completely symmetric input wiring. Asymmetric wiring yielded a degradation of more than 25dB at 20MHz. This indicates the importance of a characterization with the LISN since the set-up of a typical LISN is not symmetric at all. Furthermore, every compliance measurement set-up includes a LISN. As such, the characterization has to be done in combination with the LISN.

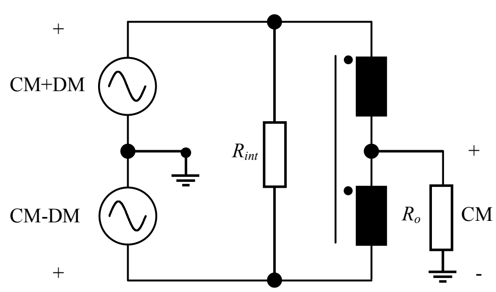

Fig. 2: 0° power combiner (see [2] for more details)

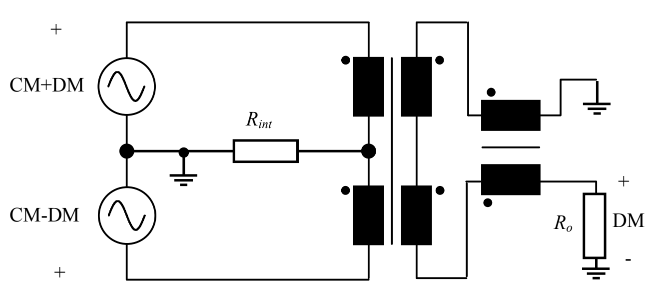

Fig. 3: 180° power combiner (see [2] for more details)

III. INVESTIGATED SEPARATION TECHNIQUE

The cm and dm noise separation technique described in this paper is similar to the second method in section II. Current probes will be used as well, but in another position to get rid of the previously mentioned problems.

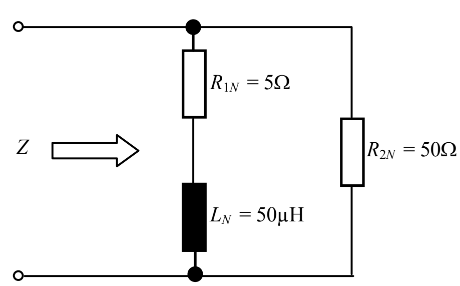

Fig. 4: Line impedance [11]

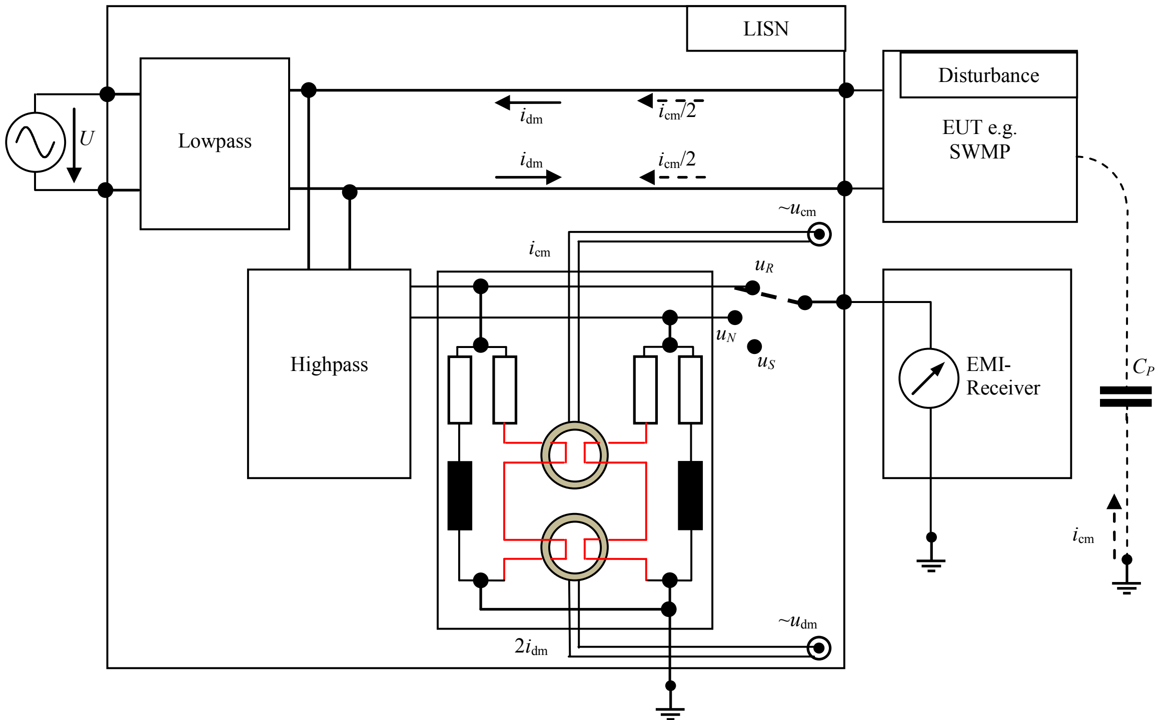

Fig. 5: V-LISN with current probes for cm and dm noise separation

The two current probes for cm and dm noise are inserted into the replication of the line impedance of a V-LISN (Fig. 4) [11], in the path of R_{2N} of Fig. 4 that represents the input impedance of an EMI test receiver. Fig. 5 depicts the implementation inside the LISN. The connection of the EMI receiver and the filter stages are only shown schematically. The upper current probe is for the measurement of i_{cm}, and the lower one for i_{dm}. The supply current for the device under test will therefore no longer flow through the current probes at this location. Furthermore, the current in the path of a resistor will be measured. Therefore, the desired voltages u_{cm} and u_{dm} are proportional to the currents i_{cm} and i_{dm}. Only a constant correction factor is needed in order to get the correct voltages u_{cm} and u_{dm}.

Another advantage of this method is the simplicity of the set-up requiring only two proper current probes. In the practical set-up the small current probes Tektronix CT2 with a frequency range of 1.2kHZ - 200MHz and a current to voltage conversion factor of 1mV per 1mA into 50Ω are used here.

Before a proper calculation of the correction factor it needs to be mentioned that the noise voltage at the line impedance is caused by $i_{cm}/2$ and i_{dm}, and due to the necessary cancellation each of these noise currents is measured twice. With this information and the current to voltage transfer ratio of the used current probes, the cm and dm EMI noise correction factor of this set-up results in

$$\frac{u_{R2N}}{u_{measure}} = \frac{1\text{mA}}{1\text{mV}}\frac{50\Omega}{2} = 25 \mathrel{\hat{=}} 28\text{dB}\,. \tag{1}$$

Therefore, a constant factor of 28dB must be added to the measured cm or dm interference level in order to get the correct voltage across the line impedance caused by either cm or dm EMI noise.

IV. Characterization of the Investigated Separation Technique

There are two main set-ups that need to be investigated in order to show that the imperfect LISN limits the rejection level. One set-up is extremely symmetric and without LISN, and the other one includes the LISN.

But before any measurements can be performed a balancing unit (balun) that is as ground free as possible is needed. Otherwise it is impossible to obtain a pure dm excitation for the LISN. For this purpose the LAN transformer 749013010 from Wuerth electronics was chosen as balancing unit.

First of all, it is extremely important to carefully measure this device with respect to its own modal conversion characteristics. The corresponding rejection ratios are obtained by means of nodal S-parameter measurements on the 3 ports of the balun. The cm-dm and dm-cm rejection is then calculated under a symmetric dm termination with two 50Ω resistors and a generator with 50Ω output impedance at

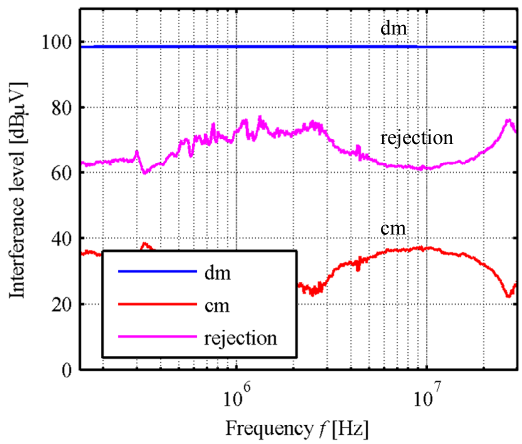

Fig. 6: Calculated rejection according to measured S-parameters of the used LAN transformer

the input of the balun. The calculation requires a determination of modal values out of nodal measurement results [12]. Fig. 6 shows the result of the calculation based on the measured S-parameters of the balun. A rejection of at least 60dB is possible with the used LAN transformer as balun. This rejection is enough since much lower rejection values occur in combination with the LISN as it will be seen in the following measurement results. Hence, the used LAN transformer fulfils his function as balun and provides an adequate ground free output. Consequently, it can be used for the characterization of the cm and dm separation technique inside the LISN.

In a next step, the current probes that are inserted into the LISN (R&S ESH2-Z5) are characterized separately within an extremely symmetric set-up, as shown in Fig. 7. The whole set-up consisting of the already mentioned LAN transformer 749013010 from Wuerth electronics as balun, the two current probes from Tektronix, and two 50Ω resistors is pretty straightforward. Fig. 8 shows the corresponding schematic for dm excitation. This measurement characterizes the cm rejection, possible in case of the proposed realization using

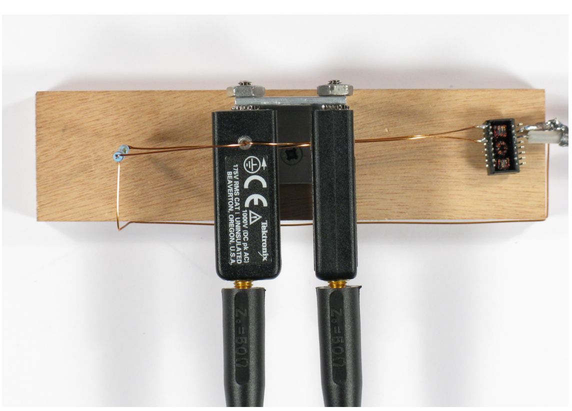

Fig. 7: Symmetric set-up without LISN

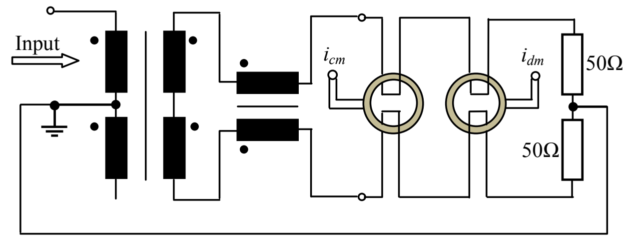

Fig. 8: Schematic of the symmetric set-up without LISN and dm excitation

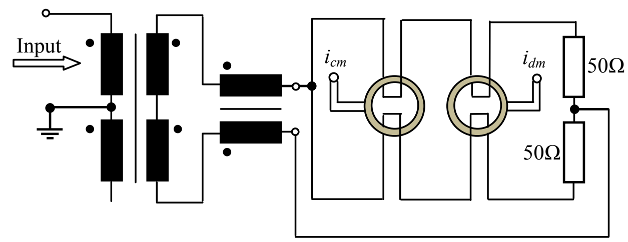

Fig. 9: Schematic of the symmetric set-up without LISN and cm excitation

two current probes and a balun. Fig 9 reveals the schematic for cm excitation. It allows a determination of the dm rejection with two current probes in a very symmetric set-up.

The results from measurements in the frequency range 150kHz to 30MHz with the symmetric set-up according to Fig. 7 and Fig. 9 are shown in Fig. 10. It reveals the dm rejection under cm excitation. A rejection of at least 60dB is achieved in the whole frequency range from 150kHz to 30MHz. Fig. 11 shows the measurement result according to the symmetrical set-up of Fig. 7 and Fig. 8. This time it is the cm rejection under dm excitation. The result of the rejection is pretty similar than before and a rejection of at least 60dB is achieved in the whole frequency range from 150kHz to30MHz. Therefore, both results show a rejection of the undesired conducted EMI noise component of at least 60dB

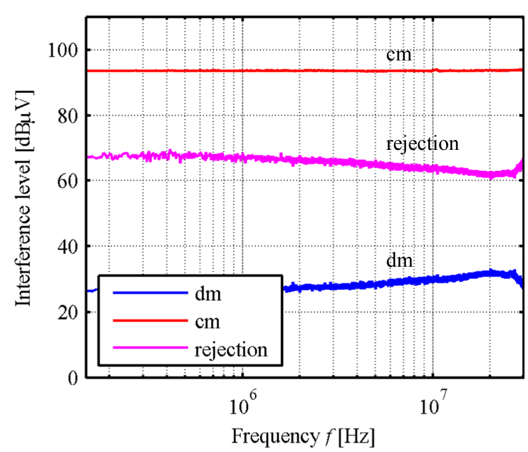

Fig. 10: Dm rejection by cm excitation of the symmetric set-up without LISN according to Fig. 7

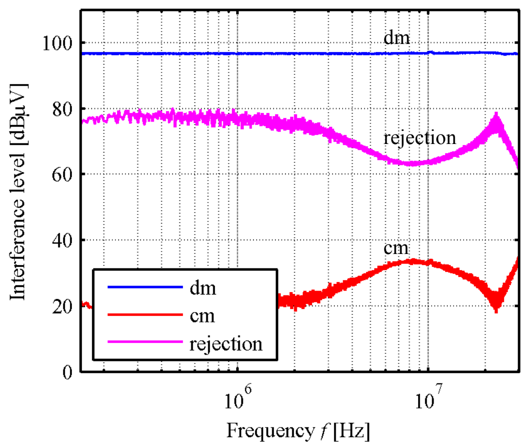

Fig. 11: Cm rejection by dm excitation of the symmetric set-up without LISN according to Fig. 7

in the considered frequency range from 150kHz to 30MHz. This rejection level is by far more than sufficient for a proper cm and dm separation.

Moreover, it has to be noted that the achieved rejection level is a result of the complete set-up including the arrangement of the wires, the 50Ω resistors, as well as the current probes. The results show that for high frequencies nearly no degradation in terms of rejection is observed, whereas for low frequencies there is an improvement. This is not astonishing since the network analyzer, which was used to measure the S-parameters of the balun, is not very accurate at lower frequencies.

However, as mentioned in section II, it is very important to characterize the full noise separation set-up including the LISN. Fig. 12 reveals a possible practical measurement set-up for cm-excitation together with the LISN and Fig. 13 the one for dm excitation. The general schematic for the set-up with LISN and cm as well as dm excitation is shown in Fig. 14. It has to be mentioned that the different excitations were realized by means of a Rohde & Schwarz tracking generator in the EMI test receiver and again the LAN

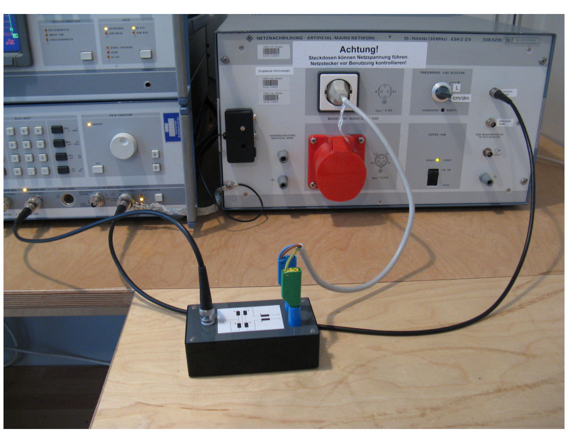

Fig. 12: Set-up with LISN and cm excitation

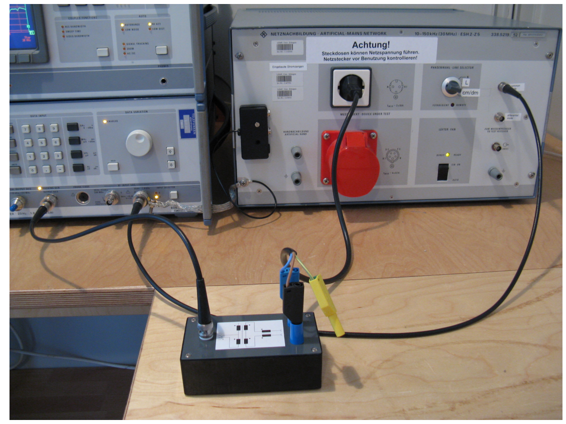

Fig. 13: Set-up with LISN and dm excitation

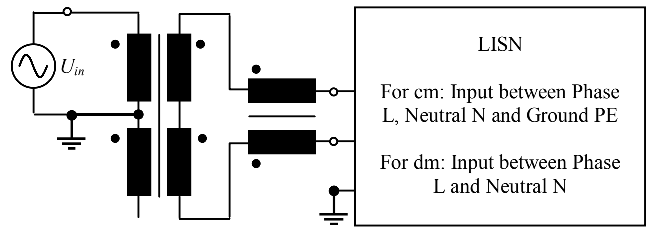

Fig. 14: Schematic of the set-up with LISN

transformer 749013010 from Wuerth electronics as the balancing unit.

Measurement results for a proper characterization of the whole set-up including the LISN can be seen in Fig. 15 and Fig. 16. Fig. 15 reveals the dm rejection under cm excitation and Fig. 16 the cm rejection under dm excitation. Both measurements are done in the same frequency range, 150kHz to 30MHz, as before. A cm and dm rejection of at least 32dB is achieved in the considered frequency range. Of course, it is lower than before compared to the symmetric set-up, but still high enough for noise diagnosis and filter design. Nevertheless, the designer should take into account that it is not perfect at all in order to prevent a misinterpretation of the measured results, because there are cases when the modal conversion within the LISN is that high that improper readings may occur. As discussed in the next section, the insertion of a dm filter can be apparently effectless in case of high cm noise.

It is of worthy note that this modal conversion is really caused by an asymmetric LISN and not given by limitations of the balun or the used current probes since the measurement results of the symmetric set-up with the same devices and arrangement reveal a much higher rejection level.

The measurement results show that only a very symmetric set-up like it is seen in Fig. 7 yields a very high rejection level. Therefore, the reason for the deterioration of the rejection after including the LISN is the asymmetry in the

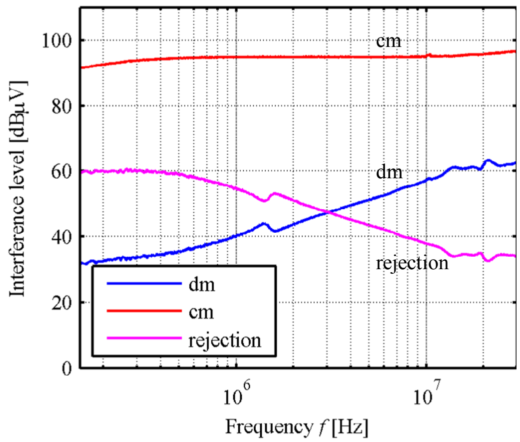

Fig. 15: Dm rejection by cm excitation in combination with LISN according to set-up of Fig. 12

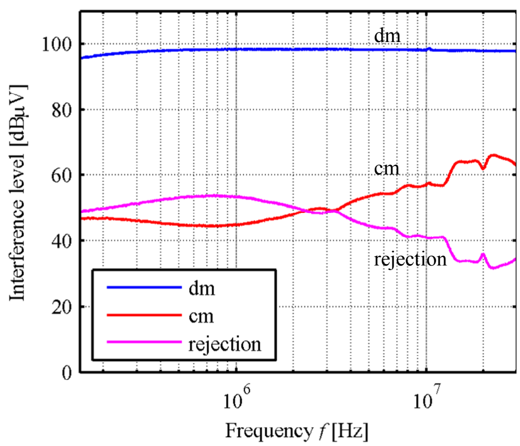

Fig. 16: Cm rejection by dm excitation in combination with LISN according to set-up of Fig. 13

LISN. A typical LISN is normally not symmetric at all and introduces the highest amount of imperfections. Again, this indicates the importance of a characterization with the LISN. But why causes asymmetry a detection of dm EMI noise current by the presence of only cm EMI noise current and vice versa? The answer to this question becomes pretty obvious after looking at Fig. 17. There is a cm current source I_{cm} together with the line impedances Z. But this time there are impedances Z_L and Z_N in series with the line impedances Z. These impedances Z_L and Z_N are a combination of parasitic and filter elements inside the LISN. If the impedances Z_L and Z_N were identical, the cm current i_{cm} would split equally in path 1 and path 2. Hence, no dm current through the line impedances would be detected. If they are not identical, like in the case of a standard LISN, the cm current i_{cm} will not split equally and more current flows either through path 1 or through path 2. Moreover, this is equivalent with a combination of a cm and a dm EMI noise current. Therefore,

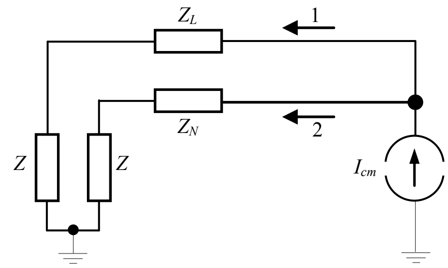

Fig. 17: Dm detection in case of cm current

the current probe for dm detection registers something even without the presence of a real dm signal at the LISN's input. The other way round (in case of a present dm EMI noise current and a missing cm one) can be explained in a similar way.

V. Measurements with a Switch Mode Power Supply

It was already mentioned that the filter designer should take the existing rejection value into account in order to prevent a misinterpretation of the measured results. There are cases with a visible modal conversion and Fig. 18 reveals such a case.

Fig. 18 shows the cm and dm measurement of a switch mode power supply (SMPS). In addition, the admissible limit given by [13] is added in green. A compliance measurement would basically have the red curve (highest one) as result since this noise level is significantly higher. However, without the discussed separation, the designer would have to guess what filter he should apply in order to reach the admissible limits. But even in case of the separation discussed at hand, the limited rejection ratio can lead to misinterpretation. The input voltage of the SMPS is 230V/50Hz and the output power is 400W for this measurement. Only a dm filter is added so far in order to reduce the dm interference level in the low frequency range below the limit. A cm filter is not added and the cm interference level is still very high over the whole considered frequency range from 150kHz to 30MHz.

The dm level in the high frequency range is still above the given limitation despite the insertion of a dm filter. Actually, this is no real dm noise. A close look reveals that it has the same shape as the cm noise level. Hence, due to the given finite rejection the very high cm noise level is visible in the measured dm noise level over the whole frequency range. Filter designer should always have that in mind in order to avoid misinterpretation of the given data. Especially during the experimental design phase of the EMI filter.

The dm interference level will reduce drastically if only the cm level is reduced. In order to show this, a measure is needed that reduces only the cm level. The used SMPS is a two stage solution. During experimentation we verified that the two stages affect the whole conducted EMI noise of the SMPS completely different. The dm noise is caused by the

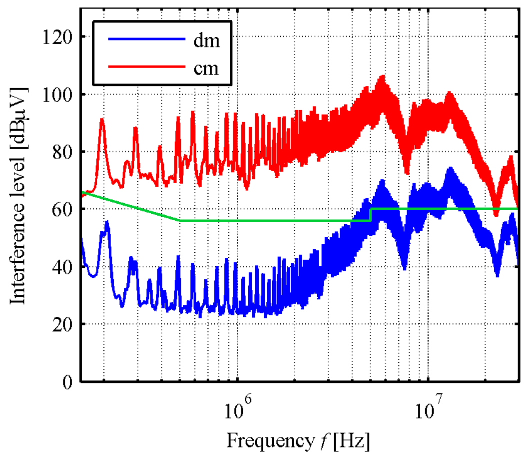

Fig. 18: Cm and dm measurement - low dm and high cm level

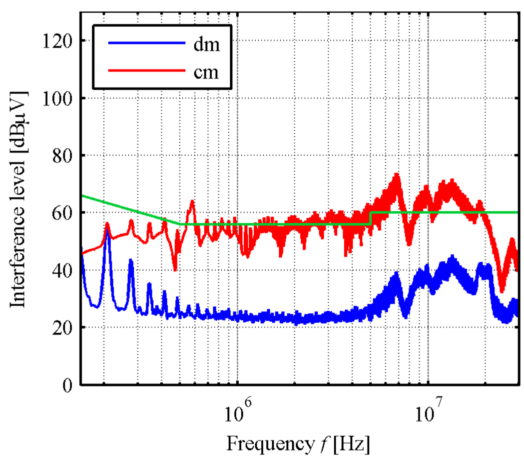

Fig. 19: Cm and dm measurement - low cm and dm level

first stage, whereas the cm EMI noise level is mainly caused by the second stage. Hence, the cm interference level can be easily reduced without changing the real dm noise by turning off the second stage. In addition, a further reduction is achieved by disconnecting the ground PE. The load is directly connected to the output of the first stage and adjusted that the input power of the SMPS is the same as before. Fig. 19 shows the corresponding measurement result. The cm interference level became much lower, as well as the dm interference level. Hence, the high dm level in Fig. 18 exists due to the high cm noise level and the given rejection level.

Nevertheless, a rejection level of around 32dB is normally more than enough. But again, system and filter designer should have in mind that a modal conversion may occur. Otherwise, the interpretation of the measurements may lead to a completely wrong filter design with too many components.

VI. Conclusion

A very simple method for the separation of common mode and differential mode noise has been described and fully characterized in the complete system. Measured results demonstrate very high rejections of the unwanted noise component for the described approach using two current probes. While measurements including the LISN exhibit somewhat lower rejection levels the complete set-up including the LISN still yields an adequate cm and dm rejection. Hence, this set-up provides the designer a valuable tool for noise diagnosis and filter design.

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