Novel Three-Phase CM/DM Conducted Emissions Separator

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Abstract — **This paper presents two novel three-phase common mode/differential mode noise separation networks, a passive and an active network, to be used in EMC conducted emission measurements of three-phase equipment. The passive network is analyzed theoretically and a prototype is constructed. Its evaluation is presented through frequency response measurements and conducted emission tests performed on a three-phase motor drive and verifies that the network is capable of separating the common and differential mode information in a CE measurement condition.**

I. INTRODUCTION

Three-phase conducted emission (CE) measurements are a major issue for developing high power electronic equipment that is connected to a commercial electric grid due to EMC concerns which are reflected in international and regional regulation. Three-phase power electronic systems, such as motor drives and high power rectifiers, must comply with these regulations. To achieve compliance the equipment must include filtering and other electromagnetic emission control strategies. The conceptualization and the dimensioning of these emission control techniques are being increasingly researched and as a result analytical and experimental tools are being developed to aid the design engineers. There, the qualitative and quantitative assessment of the noise modes, common (CM) and differential (DM) modes, is of great importance. The main objective of this work is to propose a device that can be integrated in a three-phase CE standard measurement system that allows the separate evaluation of CM and DM emission levels. This device is named the three-phase CM/DM noise separator.

Circuits that provide the discrimination of noise modes for single-phase systems have been presented in [1]-[6] and their operating principle is based on the fact that the summing and subtracting of two sensed voltages leads to the measurement of the distinct emission values for CM and DM. Other methods that use mathematical analysis through Fast Fourier Transformation [8] are used, provided that sampling rates are adequate and phase information is correctly computed.

A three-phase measurement system capable of separately measuring both noise modes is proposed in [7] and it employs current transducers and hybrid junctions. However, the drawbacks of this system are that it does not fulfill all the specifications of CISPR 16 and it requires a complex assembly for the test setup. In [8] another measurement technique is presented, which is suitable for high power levels, but it does not use a LISN and needs numerical treatment for the acquired data. Numerical models are presented in [9] which also allow for the CM and DM emission levels estimation but only if detailed model of the system is available. Another method is given in [10], which uses post mathematical processing in order to calculate the CM/DM emission values based on the noise propagation characteristics for the converter under consideration.

In this paper, a novel hardware interface between a three-lines LISN and an EMC test receiver is proposed, thus allowing a real-time direct measurement of DM and CM emission levels in a typical CISPR 16 specified setup [11], [12].

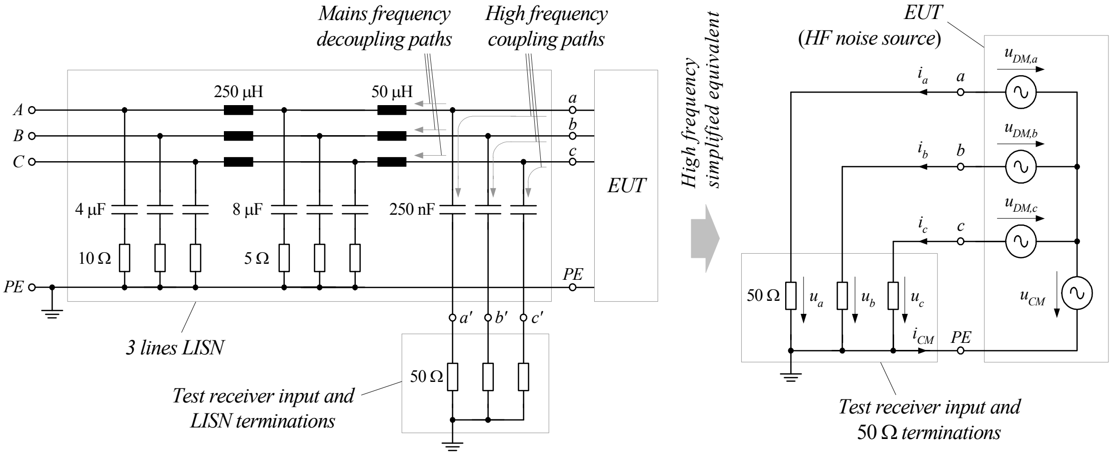


Fig.1: Typical three-phase CE measurement setup schematic and high frequency simplified circuit.

In Section II a short discussion on CE measurements in three-phase systems and the relationships between measured voltages and noise modes are presented, and this provides the analytical basis for the CM/DM separation in three-phase systems. Two basic circuit topologies – a passive and an active one – for three-phase CM/DM separation networks are proposed in Section III and the passive one is analyzed. A hardware realization of the passive circuit is discussed in Section IV and experimental results, illustrating the performance of the hardware prototype, are given in Section V.

II. THREE-PHASE CONDUCTED EMISSION MEASUREMENTS AND NOISE COMPONENTS

In order to evaluate equipment for compliance to CE noise limits a Line Impedance Stabilization Network (LISN) is usually utilized. Basically, the LISN has to fulfill the following three functions: defining the mains impedance in order to standardize the measurement; decoupling the low frequency AC power supply voltage from the measurement equipment and; providing a high frequency coupling path between the equipment under test (EUT) and a measurement test receiver.

The impedance curve of a LISN is defined by EMC standards, for instance as in CISPR 16 [13]. A typical realization of a three-phase LISN circuit is depicted in **Fig.1**. For the CE measurement process a test receiver with 50Ω input impedance is connected to one of the LISN channels while the remaining two LISN ports are terminated with 50Ω creating symmetric measurement conditions.

Assuming, at high frequencies, an ideal decoupling from the EUT to the mains and a perfect coupling with the test receiver, which is the case for the circuit of Fig.1 in a simplified consideration, the equivalent high frequency circuit (Fig.1) is obtained and used in the following analysis. There, the input ports *a*, *b* and *c* of the EUT are directly connected to the input ports of the test receiver what means that all high frequency noise from the EUT is coupled to the test receiver, while the mains ports *A*, *B* and *C* are separated from the EUT.

The measured voltages u_i (with $i=a, b, c$) at the test receiver 50 Ω sensing resistors comprise both a differential mode and a common mode component

$$u_i = u_{DM,i} + u_{CM} \,. \tag{1}$$

These two components are caused by the three differential mode currents $i_{DM,i}$ and a common mode current i_{CM} circulating between the EUT and the test receiver. For a symmetric distribution of i_{CM} between the three phases the currents i_i flowing to the test receiver input ports are

$$i_i = i_{DM,i} + \frac{i_{CM}}{3} \,. \tag{2}$$

Due to the fact that the sum of the differential mode currents is, per definition, equal to zero

$$i_{DM,a} + i_{DM,b} + i_{DM,c} = 0 \,, \tag{3}$$

the sum of the currents to the test receiver equals the common mode current

$$i_a + i_b + i_c = i_{CM} \,. \tag{4}$$

Therefore, the common mode voltage can be evaluated by the summation of the measured voltages

$$u_a + u_b + u_c = R \cdot \left(i_a + i_b + i_c\right) = R \cdot i_{CM} = 3 \cdot u_{CM} \,. \tag{5}$$

For evaluating the differential mode components the common mode part has to be eliminated. This can be achieved directly by the subtraction of two test receiver voltages

$$u_a - u_b = u_{DM,a} - u_{DM,b} \,. \tag{6}$$

With (5) and (6) one can realize that a separated evaluation of the common and differential mode components in a three-phase system is achievable through proper mathematical formulation. This results in the development of electrical networks as presented in **Fig.2**.

III. THREE-PHASE CM/DM NOISE SEPARATION NETWORKS

In order to practically implement the mathematical formulation given in the previous section and properly separate both noise modes using an electrical network two circuit topologies are proposed in Fig.2 [14]. Fig.2(a) shows a passive solution which is

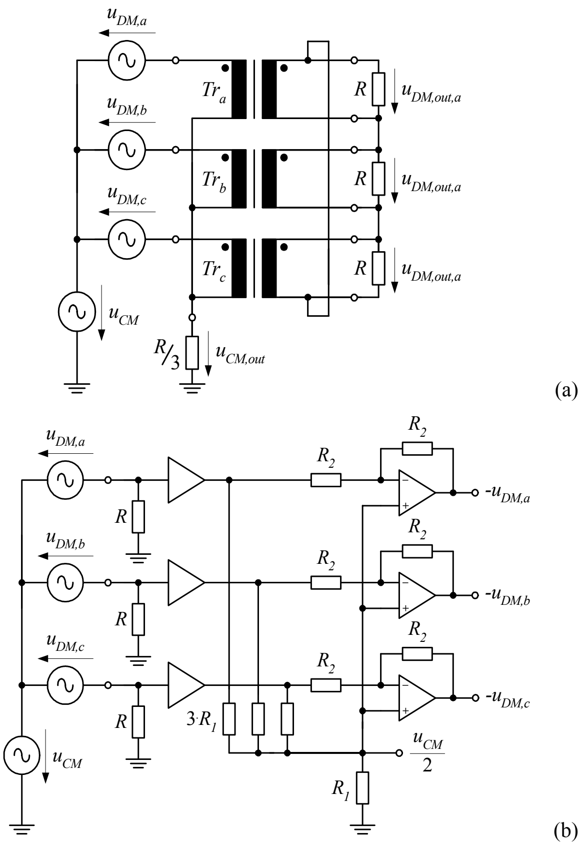


Fig.2: Three-phase CM/DM noise separator proposals [14]. (a) Passive solution. (b) Active solution.

analyzed in detail in this paper. The circuit of Fig.2(b) uses active elements and will be analyzed in a further publication. In the figures the high frequency noise components are depicted by a common mode voltage source u_{CM} and three differential mode voltage sources $u_{DM,a}$, $u_{DM,b}$ and $u_{DM,c}$.

A network that makes use of active circuits would require amplifiers with very large bandwidths and high power supply rejection ratios, and the design of a suitable amplifier power supply. However, the active solution would provide well defined input impedances and a good control of the insertion loss allowing required adjustments to be done easily.

The passive solution comprises of three transformers Tr_a, Tr_b and Tr_c with star-connected primaries, delta-connected secondaries and one-to-one turns ratio. The primary side star-point is connected to the ground via a resistor $R/3$ while the secondaries are terminated by resistors R.

The mathematical analysis of the circuit helps to clarify the noise separation effect. Equations (7) and (8) are obtained from the circuit.

$$u_{CM} + u_{DM,i} - u_{DM,out,i} = u_{CM,out} \tag{7}$$

$$\sum_{i=1}^{3} u_{DM,out,i} = 0 \tag{8}$$

According to the definition of the differential mode voltage sources and based on the fact that the termination impedances R_a, R_b and R_c are balanced it follows that:

$$\sum_{i=1}^{3} u_{DM,i} = 0 \tag{9}$$

The summing of the three equations included in (7) leads to equation (10).

$$u_{CM} = u_{CM,out} \tag{10}$$

By replacing (10) in (7) gives (11):

$$u_{DM,i} = u_{DM,out,i} \tag{11}$$

Based on (10) and (11) it is clear that the proposed network provides in its output ports the values for the differential and common mode voltages.

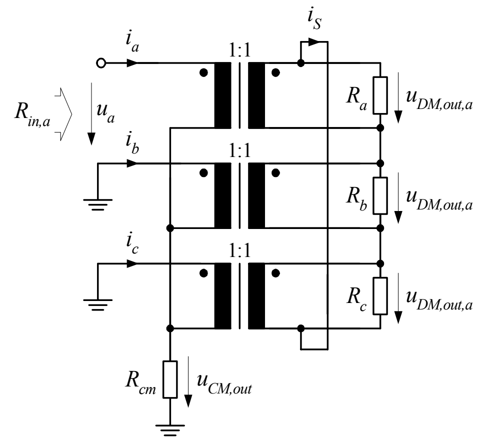


Fig.3: Circuit used for the calculation of the input impedances to ground.

Another relevant issue for the measurement setup is the value of the input impedances of the network since the CE measurements with a LISN usually demand 50 Ω balanced sensing resistors. Since the network is symmetric the analysis of the input impedances is done with the help of **Fig.3** for only one of the inputs.

By solving the circuit equations one gets to equation (12).

$$\frac{u_a}{i_a} = 9 \cdot \frac{R_a \cdot R_b \cdot R_c \cdot R_{CM}}{R_a \cdot R_b \cdot R_c + R_{CM} \cdot \left[4 \cdot R_b \cdot R_c + R_a \cdot \left(R_b + R_c\right)\right]} \tag{12}$$

In order to have a balanced circuit the resistors R_i have to be made equal:

$$R_a = R_b = R_c = R \tag{13}$$

Replacing (13) in (12) results in (14).

$$R_{in,a} = \frac{u_a}{i_a} = \frac{9}{\frac{6}{R} + \frac{1}{R_{CM}}} \tag{14}$$

Since the DM output ports will be sensed with the resistance R and this will be done in a test receiver with an input resistance of 50 Ω it is desirable that the input resistance present the same value, i.e. $R_{in}=R$. Solving (14) gives (15):

$$R_{CM} = \frac{R}{3} \tag{15}$$

Based on the presented analytical equations it is certain that the proposed network is able to perform the separation of CM and DM conducted emission levels in a standard measurement setup.

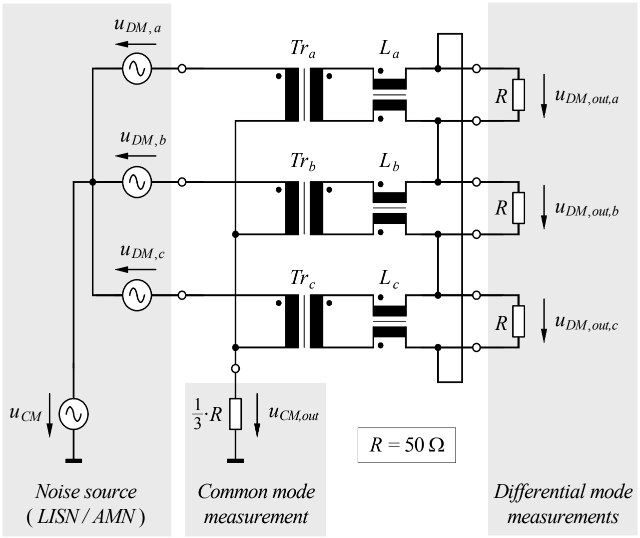


Fig.4: Circuit schematic of the three-phase CM/DM noise separator.

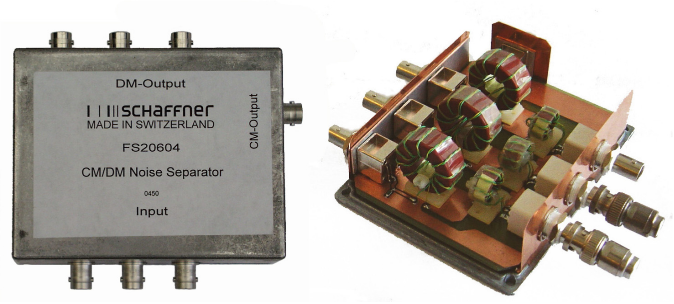


Fig.5: Three-phase CM/DM separator prototype photograph. Overall dimensions: 12.0x9.5x5.7 cm (4.75x3.75x2.25 in.).

IV. THREE-PHASE CM/DM NOISE SEPARATOR REALIZATION

In order to implement the three-phase CM/DM noise separator presented in the previous section the schematic in **Fig.4** is used. The separator is specified to be used in a standard CISPR 16 CE test setup using a typical (50 µH+5 Ω)//50 Ω V-network LISN and applying input line-to-line voltages of 400 V / 50 Hz.

The noise separator is built with the network formed by the transformers Tr_a, Tr_b and Tr_c and the inductors L_a, L_b and L_c. Employing $R = 50\,\Omega$ ensures an equivalent resistance of the noise separator inputs to ground of 50 Ω and allows the measurement of the CM and DM noise voltages directly from the respective output ports. For measuring a differential mode noise voltage the corresponding output is connected to the input of the test receiver (input impedance of 50 Ω) after removing the explicit resistive termination. Considering parasitic coupling capacitances of the transformers the measurement with reference to ground causes an asymmetry of the circuit which could result in a transformation of CM into DM noise. In order to achieve a higher common mode rejection ratio (CMRR), therefore common mode inductors L_a, L_b and L_c, ensuring equal impedances of the transformer output terminals against ground for high frequencies, are inserted into the differential mode outputs. A photo of a first practical realization of the three-phase CM/DM noise separator is shown in **Fig.5**.

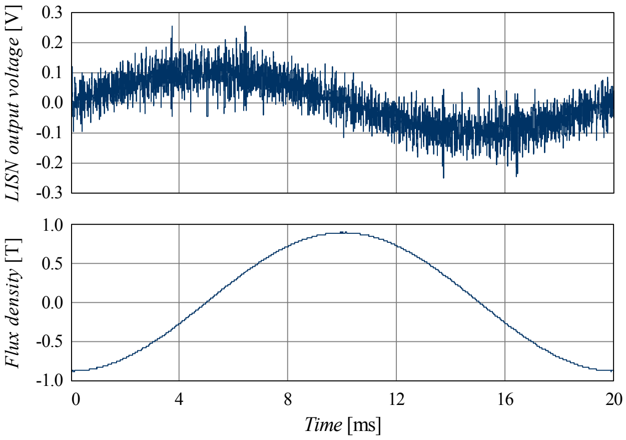


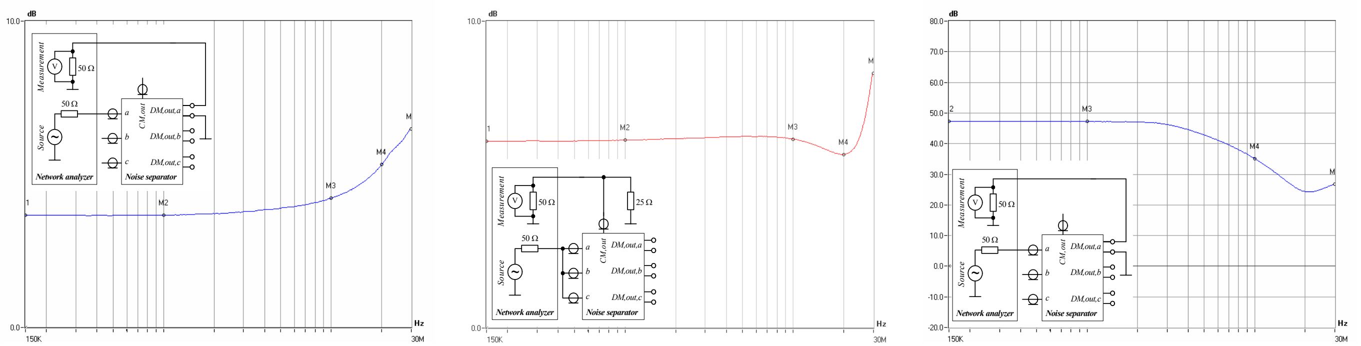
Fig.6: Calculated flux density in the designed transformers Tr_a, Tr_b and Tr_c, for a simulated LISN output voltage when feeding a three-phase 5 kW rectifier.

In order to construct the transformers in the separator some requirements must be fulfilled, namely: the 50 Hz component present in the LISN output and the maximum CM signal levels should not cause the saturation of the core; leakage inductance must be small in order not to influence the gains; primary to secondary capacitance values should also be as small as possible in order to prevent CM paths to the secondary; good coupling should be guaranteed for low and high frequencies. Aiming for these characteristics the material VITROPERM 500F from Vacuumschmelze GmbH (VAC) was chosen, presenting a high maximum saturation flux density ($B_{max} \cong 1.2$ T) and good high frequency characteristics. The transformer is built with a VAC 25x16x10–T6000-6-L2025-W380 core with 10:10 turns of twisted insulated wires. **Fig.6** shows a calculation result for the flux density in the core for the designed transformers Tr_a, Tr_b and Tr_c when the LISN is feeding a three-phase rectifier supplying 5 kW and switching at 20 kHz. The CM chokes in the separator prototype are built with the same core material as the transformers using a smaller core (VAC 12.5x10x5–T6000-6-L2012-W498), and presenting a CM inductance around 1 mH.

For applying the separator, a three or four line LISN must allow simultaneous access to all three-phase output ports. In case this is not possible, three individual single-phase LISNs could be employed. All asymmetries presented in the test circuit composed of the LISN and the noise separator will influence the measurements, especially in the higher frequency range and should be avoided.

V. EXPERIMENTAL EVALUATION

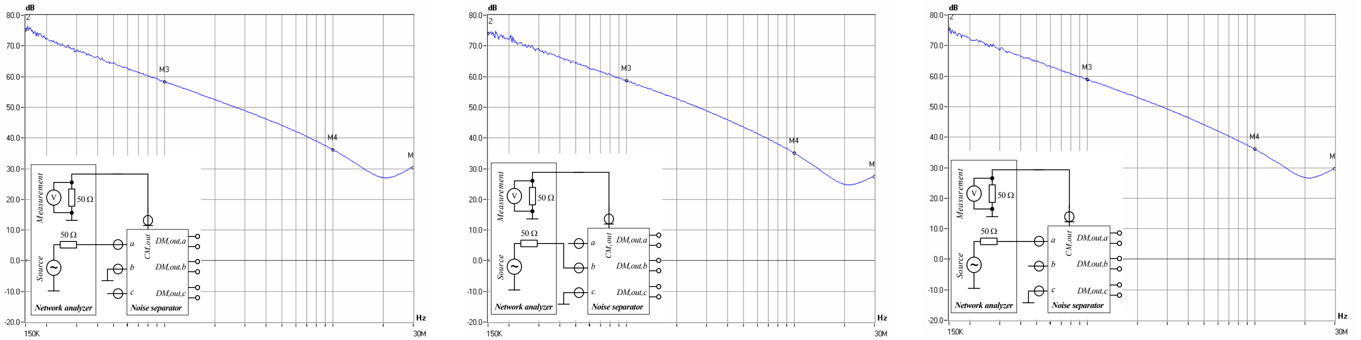
Some of the frequency response characteristics of the prototype were measured with a impedance and network analyzer in order to evaluate the design. These measurements were performed with 50 Ω input and output impedances. The most significant results of these measurements are shown in **Fig.7**. The insertion loss (calculated from the measured attenuation using the 50 Ω source/sense setups shown in Fig.7) curves for the three DM channels are quite similar and only one is presented in Fig.7(a) where the presented -3 dB cutoff frequency is higher than 20 MHz and good symmetry amongst the channels is observed. In Fig.7(b) the gain between a measured CM output voltage and a CM input signal is plotted and again a flat band up to more than 20 MHz is observed. As the noise separator is intended to discriminate common and differential modes it is important to check how good the attenuation of the other noise components is, for instance, when measuring a CM signal the influence of the DM channels is needed to be known. This can be evaluated through the measurement of the differential mode rejection ratio (DMRR) of all channels and of the common mode rejection ratio (CMRR) for the DM channels. As the DMRRs of the DM channels is very similar it is presented in Fig.7(c) using only one measurement that was performed for the DM output port C with the input signal applied between input ports A and B. The DMRRs of the CM port are shown in Fig.7(d)(e)(f) and for all cases is higher than 70 dB at 150 kHz and higher than 25 dB up to 30 MHz. The CMRR of the DM output ports is presented in Fig.7(g)(h)(i) show-



(a) DM insertion loss for channel *a*

(b) CM insertion loss

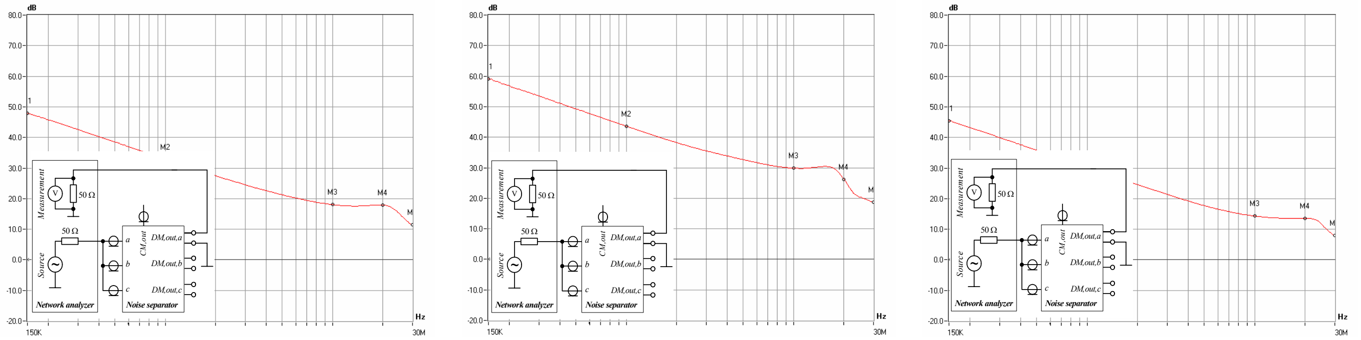
(c) DMRR for DM output port *c*
(input signal: ports *a* and *b*)



(d) DMRR for CM output port
(input signal: ports *a* and *b*)

(e) DMRR for CM output port
(input signal: ports *b* and *c*)

(f) DMRR for CM output port
(input signal: ports *a* and *c*)



(g) CMRR for DM output port *DM,out,a*

(h) CMRR for DM output port *DM,out,b*

(i) CMRR for DM output port *DM,out,c*

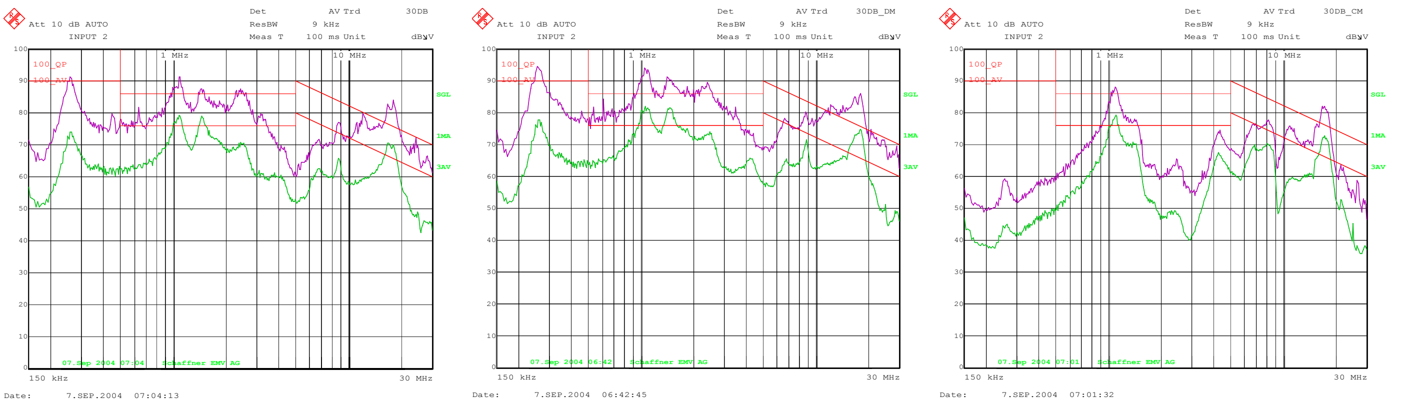
Fig.7: Measured frequency characteristics for the CM/DM noise separator. All ordinate axes present 10 dB per division. Frequency range: 150 kHz to 30 MHz.

ing around 50 dB in the lower frequency range and being around 20 dB at 10 MHz. The measured frequency characteristics show that the noise separation network performs its task mainly in the frequency range up to 10 MHz. However, a better performance for higher frequencies is desirable so that rejection ratios in the order of 30 dB at 30 MHz guarantee a clear separation of the noise modes. This could be achieved with a more symmetrical layout and components with improved HF performance.

Conducted emission measurements as specified in CISPR 16 were performed utilizing a setup as shown in **Fig.9** in order to give an example for the use of the three-phase CM/DM separator. The EUT was a regenerative drive feeding a 10 kW motor. The test conditions were as follows: input voltages U_{in}=400V/50Hz; output power P_{out}= 5 kW. The LISN conforms with CISPR 16, is constructed to operate from 2 kHz to 30 MHz and is presented in [15]. The access to all output ports is available, thus guaranteeing that the three-phase CM/DM noise separator can be used.

Fig.8 shows the acquired data for three measurements done within the same operating conditions, one without the noise separator Fig.8(a), the second showing the measured emission levels sensed in one of the DM channels with the presented network Fig.8(b) and the last one depicts the measurement performed in the CM output port.

From the measurements one can see that there is a large difference between the levels of DM and CM emissions in the lower frequency range with the DM emissions being much higher than the CM ones up to5 MHz. This indicates the necessity of higher DM attenuation at this frequency range. It also shows how much attenuation is required and this allows an appropriate filter to be designed. With this example the main purpose of the separator network, which is



(a) Direct LISN measurement (phase A)

(b) DM separator output (phase A)

(c) CM separator output

Fig.8: Measurements performed with and without the noise separator. Axes: 0 to 100 dBμV and 150 kHz to 30 MHz. Upper curves: quasi-peak measurement as specified in CSIPR 16. Lower curves: average detection measurement. (a) Measurements applying directly a LISN; (b) Measurements performed in one noise separator DM output port;(c) Measurements from the noise separator CM output port.

acquiring information for filter designs and troubleshooting of power converters, is proved through experimental results.

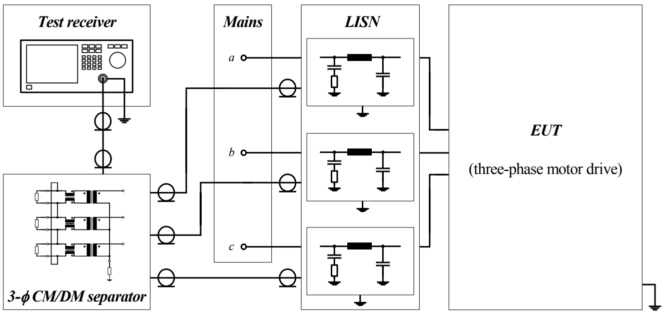


Fig.9: Test setup for the conducted emission measurements using the proposed three-phase CM/DM noise separation passive network.

VI. CONCLUSIONS

This paper has presented two novel three-phase DM/CM separation networks that are intended to be used in the evaluation of noise sources, which will help in the design and troubleshooting of electromagnetic emission control systems for electronic equipment. One network is an arrangement of passive components while the other is based on the use of active circuits. The operating principle and characteristics of the passive network were discussed and experimentally verified. Conducted emission measurements were successfully performed in a three-phase electric motor drive using the separator indicating the noise levels and dominating modes. This information could be employed to design the CM and DM stages of an EMC filter.

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