Linearity Evaluation of Voltage-Based Drive Side Three-Phase CM/DM Separation

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***Abstract*—CM/DM-separation on the load side of inverters is a rarely considered but important aspect for the determination of conducted emissions. The presented setup measures the separated voltages with an EMI test receiver. It exploits operational amplifiers and thus the linearity must be investigated in detail. A worst-case approximation verifies the good performance of the setup.**

***Keywords*—Electromagnetic Compatibility, Inverters, Linearity, CM/DM Noise separation**

I. Introduction

Investigations of electromagnetic compatibility (EMC) of inverter systems typically focus on the mains side, where regulations for conducted emissions apply. For higher frequencies, the restrictions apply to radiated fields and thus the whole system needs to be considered. In addition, the often neglected conducted emissions on the drive side of an inverter can be of critical importance for the long-term operation.

Conducted emissions on the drive side are a main cause for bearing currents, which affect the lifetime of the drive. In combination with long motor cables, these high frequent signals can cause over voltages and thus damage the motor [1], [2]. Oversizing the electrical machine can resolve these issues e.g. by increasing the insulation capability. However, these measures tackle only the negative effects of the electromagnetic interference (EMI) and reduce neither the amount of EMI generated by the inverter nor the conducted emissions on the drive side.

A method, to achieve the latter, is the introduction of an EMI filter on the load side of the inverter. While the additional filter components increase the costs for the inverter system, they can ease the requirements for the motor. Additionally, expenses for material and installation can by reduced by using unshielded motor cables. Naturally, this requires low EMI in order to comply with radiated emission requirements. Furthermore, in the case of sensible environments (precisely category C1) and long cables (more than 2 meters), regulations apply to conducted emissions on the drive side as well [3]. Thus, using EMI filters on the load side of the converter represents an interesting investment.

An even better approach is to reduce the emissions by improvements to the inverter layout. It offers the same benefits as filtering without the additional costs and volume for the filter. Knowledge about mode and frequency of emissions in combination with insights into the circuit help finding the sources.

For both cases, the filter design and the identification of EMI sources, a reliable separation between common (CM) and differential mode (DM) provides important information. It helps to adapt the filter e.g. in form of CM-chokes and it offers the possibility to find sources depending on the coincidence of frequency and mode. While this approach is very common for single [4] as well as three-phase [5] grid-side measurements, there are only a few approaches on the load-side of an inverter [6]–[8]. Based on the same basic principle, the challenges are different, since neither the defined impedance nor the integrated high-pass filter of the line impedance stabilization network (LISN) that is used on the grid side are available on the load side.

The contribution of this paper to the issue is the investigation of a voltage-based measurement setup with focus on non-linear distortions at higher voltage levels. Small-signal performance including transmission and rejection ratios is presented in [7].

II. Separation

The separation of single-phase systems in CM and DM is very common. In the decomposition, CM represents the current share that follows the (often parasitic) path to protective earth (PE) while DM flows in Line and Neutral. These definitions are very useful, as the generation and coupling mechanisms are different for both modes and thus the different parts are filtered with different components.

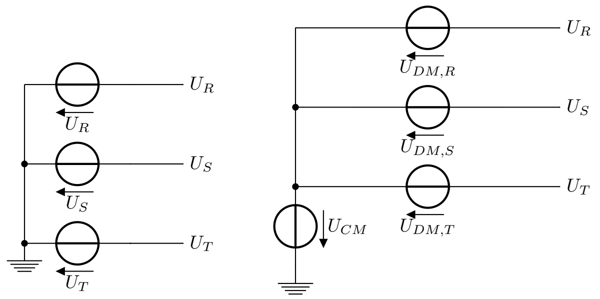
The application of an equivalent procedure on three-phase-systems needs a third component due to the additional line. The definition of CM resembles the single-phase case. It represents the voltage caused by the current through PE. Therefore, the additional mode is a second DM. This paper uses even a third DM in favor of a symmetric definition. Fig. 1 depicts the normal and the separated voltage distribution.

Mathematically, the conversion is calculated with

$$\begin{aligned} U_{CM} &= \frac{1}{3}\left(U_R + U_S + U_T\right) \\ U_{DM,R} &= U_R - U_{CM} \\ U_{DM,S} &= U_S - U_{CM} \\ U_{DM,T} &= U_T - U_{CM}. \end{aligned} \tag{1}$$

The third DM leads to an overdetermined system of equations. The application of the additional equation

$$0 = U_{DM,R} + U_{DM,S} + U_{DM,T} \tag{2}$$



(a) Normal (b) Separated

Fig. 1. Models of the inverter

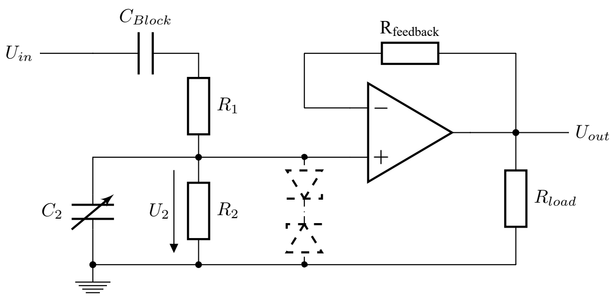


Fig. 2. Voltage divider

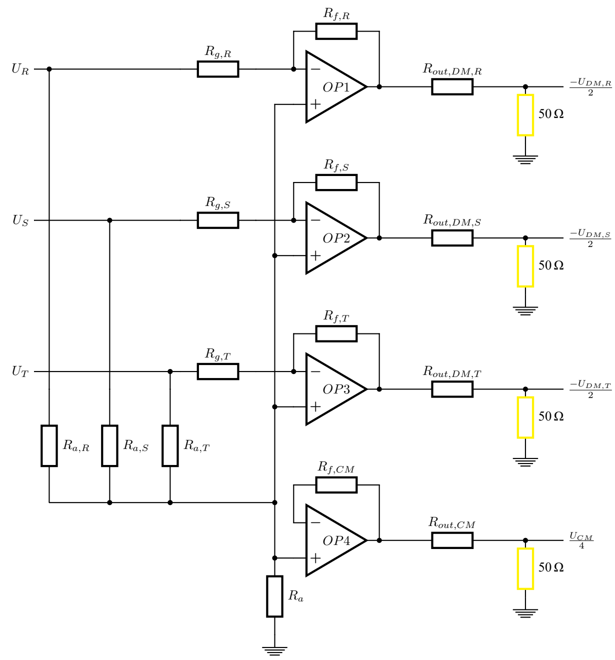


Fig. 3. Separation circuit

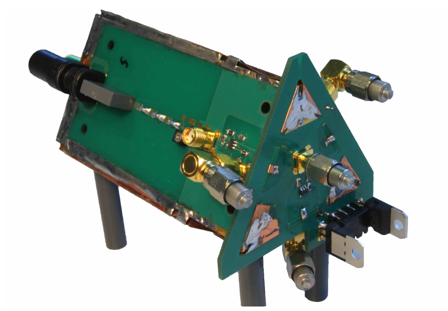


Fig. 4. Prototype

resolves this issue and describes the fact, that DM voltages cannot generate CM current in case of a symmetrical load.

III. Circuit

This paper chooses an approach based on operational amplifiers (opamps) [7]. The whole separation setup comprises two parts. The first step is the division of the high output voltage of the inverter to an appropriate level for the opamps. This part is unique to the load side of the inverter because, in difference to the grid side, no LISN is applicable. The high-impedance voltage divider does not provide the asymmetric impedance of the voltage probe required by [3], which can be added externally if desired. The second circuit separates the scaled down voltages by an interaction of several opamps similar to the grid side [5]. A EMI test receiver measures the resulting separated voltages.

Fig. 2 shows the voltage divider. The resistances R_1 and R_2 scale down a maximum line to ground voltage of 400 V to 5 V. The capacitor C_{Block} offers the possibility to keep the low-frequency supply voltage away from the separation circuit. It is designed to form, in combination with the resistances, a high-pass filter with a cutoff frequency below 9 kHz, the lowest measurable frequency of the test receiver. More details can be found in [6].

Three voltage dividers feed the separation circuit that reproduces the equations of (1). Fig. 3 depicts the wiring. The optimal operation of the opamps specifies the resistors values. [7] discusses this circuit in more details including measurements of the transducer factors. All scaling that is introduced by the prototype in Fig. 4 is reflected by the transducer factor of the test receiver.

IV. Linearity

While the functionality of the separation setup is proven for small signal excitation in [7], non-linear behavior can still impair the performance of the separation circuit.

If a linear circuit is excited by a pure sine, all currents and voltages are sinusoidal with the same frequency. This is not the case for non-linear circuits, where in general every frequency can be generated. E.g., a half-bridge generates a square wave signal out of a DC voltage. However, a typical behavior of amplifier circuits, like the opamps in the separation circuit, is the generation of sines with multiples of the exciting frequency.

For the measurement setup, these harmonics of the fundamental frequency can cause faulty results leading to overdimensioned filters and the search for non-existent EMI sources.

A particularly interesting case occurs if the fundamental frequency is a bit lower than 150 kHz, a typical starting frequency for EMI measurements. Thus, the perturbation at the fundamental frequency is of no concern for a compliance with the standard [3]. However, the harmonics of this frequency fall into

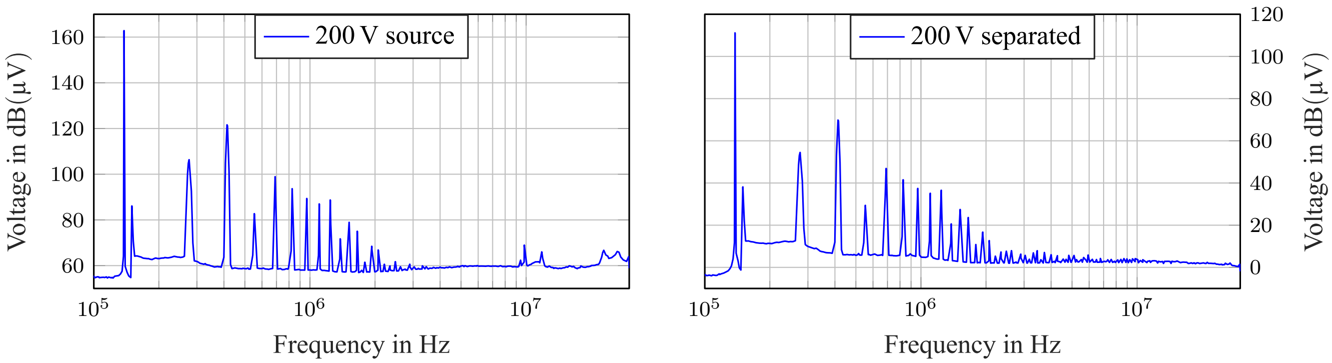


Fig. 5. Measurements for a 200 V, 138 kHz excitation with an amplifier. The left side shows the measured input voltage U_{in}. The right side depicts the corresponding separated DM voltage.

the considered frequency range and therefore nonlinearities can lead to completely wrong estimations of the interference level and therefore insufficient or superfluous filtering efforts. To emulate this worst-case scenario, the fundamental frequency of the test signal is chosen to 138 kHz.

The ideal signal for a measurement of the linearity is an excitation with a very pure sine. The voltage source is an arbitrary waveform generator with a 16 bit resolution, the Agilent 33522A, which generates sines up to 10 V peak to peak. The amplifier PFL720 from Rohrer increases this signal amplitude. The purity of the amplified source signal is measured with the test receiver using a voltage divider. For the separation setup, the source voltage is applied between one phase and ground. The linearity is quantified by measurement of the corresponding DM voltage, which is $2/3$ of the scaled down voltage U_2 in Fig. 2. Including these factors, the expected transfer ratio is approx. -51.5 dB almost independent of the frequency [7].

Fig. 5 presents the measured spectra for an excitation with 200 V amplitude which reflects the AC part of 400 volts line to ground voltage. The left side of the figure proofs that the fundamental frequency is dominant but the source exhibits additional harmonics with a much lower amplitude. These limit the possibility to evaluate the harmonics generated by the separation setup on the right side.

A comparison of the calculated and measured amplitudes for different input voltage levels in TABLE I shows that the transducer factor of the separation circuit suffices for the explanation of the measured harmonics and thus that the non-linearity of the separation setup is at least substantial lower than the harmonics generated by the source.

The simplest method for an improvement of the source voltage quality is to omit the amplifier and apply the Agilent source directly. Of course, it cannot produce sufficiently high voltage levels. Though, if the voltage is applied directly as U_2 to the output resistance R_2 of the voltage divider in Fig. 2, a much lower level is required. This naturally implies that the voltage divider itself does not suffer from non-linearity, a very plausible assumption.

The voltage divider reduces the voltage by 42 dB and therefore the 200 V signal can be substituted by approx. 1.5 V peak

TABLE I
COMPARISON OF CALCULATED AND MEASURED AMPLITUDES FOR EXCITATIONS WITH AMPLIFIER

U_{in}		Fundamental	Second Harmonic	Third Harmonic
50 V	Calc.	99.3 dB	23.7 dB	27.9 dB
	Meas.	99.2 dB	21.6 dB	30.5 dB
100 V	Calc.	105 dB	38.6 dB	49.1 dB
	Meas.	105 dB	37.4 dB	49.4 dB
200 V	Calc.	111 dB	54.8 dB	69.6 dB
	Meas.	111 dB	54.5 dB	69.3 dB

voltage. Fig. 6 depicts the voltages for direct measurements with the arbitrary waveform generator. It is clear, that the modified setup offers improved signal quality as the harmonics of the input voltage are smaller compared to the measurement with the amplifier. The difference is 85 dB for the second and 75 dB for the third harmonic even for the highest input level (1.5 V), which is approx. 30 dB better than the amplifier signal. These reductions also lead to reduced harmonics for the separated voltage. The comparisons in TABLE II reveal increased differences between calculated and measured voltages, especially for the third harmonic. Remarkable is the fact that the separated voltages have smaller harmonics than the input signal, even when the transducer factor is considered. The first suspicion, a frequency dependence of the transducer factor, is disproved by a measurement with an increased fundamental frequency. Therefore, the only remaining explanation is that the separation setup introduces an additional harmonic with a phase-shift φ compared to the harmonics introduced by the source [1].

As the test receiver cannot measure phase relations, only estimations are possible. The biggest cancellation occurs when $\varphi = 180°$ with the relation

$$|U_{meas}| = |U_{source} - U_{sep}| \quad (3)$$

for one harmonic, which has two solutions in the form of

$$|U_{sep}| = |U_{source}| \pm |U_{meas}| . \quad (4)$$

[1] This cannot explain the increased voltage peak at 150 kHz that needs further investigation.

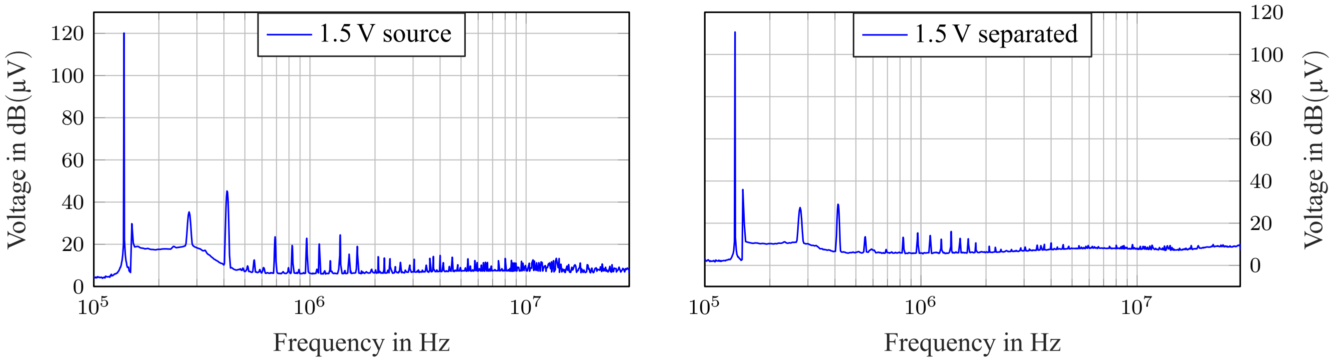


Fig. 6. Measurements for a 1.5 V, 138 kHz excitation with the arbitrary waveform generator. Left: measured voltage U_2. Right: separated DM voltage.

TABLE II
COMPARISON OF CALCULATED AND MEASURED AMPLITUDES FOR DIRECT EXCITATIONS WITHOUT AMPLIFIER

U_2		Fundamental	Second Harmonic	Third Harmonic
0.5 V	Calc.	101 dB	17.6 dB	19.7 dB
	Meas.	101 dB	14.5 dB	12.4 dB
1.0 V	Calc.	107 dB	23.4 dB	29.5 dB
	Meas.	107 dB	22.8 dB	20.3 dB
1.5 V	Calc.	111 dB	25.8 dB	35.3 dB
	Meas.	111 dB	27.4 dB	28.5 dB

TABLE III
ESTIMATED DIFFERENCE BETWEEN HARMONICS AND FUNDAMENTAL

	Second Harmonic		Third Harmonic	
U_2	Δ_{min}	Δ_{max}	Δ_{min}	Δ_{max}
0.5 V	78.9 dB	94.0 dB	78.3 dB	86.3 dB
1 V	78.0 dB	107 dB	75.1 dB	81.5 dB
1.5 V	78.0 dB	98.6 dB	72.1 dB	80.8 dB

Thus, in case of $+$, the harmonic from the separation circuit is reduced by the harmonic of the source and in case of $-$, the seperator's harmonic reduces the one from the source. The application of these assumptions on the measured data leads to the values in TABLE III.

For the second and third harmonic, the difference

$$\Delta = |U_{sep,fundamental}| - |U_{sep,harmonic}|, \tag{5}$$

which quantifies fake signals generated by nonlinearities, is at least 78 dB and 72 dB, respectively. While these values are not perfect, the results are well-suited for real world applications since pure sinusoidal interferences are a very rare case. Thus, the inaccuracy of the measurement is negligible analogue to the first measurements in Fig. 5.

V. CONCLUSION

As discussed in the beginning, a CM/DM separation on the load-side of an inverter presents a very valuable tool for the identification of dominant conducted emission modes. This information can be used either for an optimization of filters or to identify the sources and therefore trigger an optimization of the inverter design.

This paper presents a voltage-based approach for the separation. It uses a voltage divider and several opamps to generate signals for the test receiver.

The use of opamps might exhibit problems due to non-linear behavior, which would be most conspicuous in form of harmonic distortions. Thus, the linearity is verified by a measurement of a pure sine.

However, the purity of the generated sine is limited and allows only for an estimation of the suppression. Nevertheless, a possible worst-case estimation reveals with 72 dB a sufficiently large difference between the fundamental and the third harmonic. Thus, the proposed setup offers a very good performance for the separation on the load-side of inverters.

ACKNOWLEDGMENT

The authors would like to thank Philipp Konarski and Norbert Altmann for their participation in the circuit design.

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