Efficient Characterization of RF Sources for the Design of Noise Suppression Filters

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Abstract— **The filter development process, to reduce occurring conducted emissions, is still an unsolved problem within EMC considerations, due to the filter attenuation depends on the impedance values of the device under test. The paper presents a method how to characterize arbitrary active applications within the frequency domain. The evaluated noise sources are described as Y or Z- matrices with additional active sources in respect to Thevenin's law. Through a translation from the time into the frequency domain even circuits including non-linear elements can be considered. The method is presented for the example of a power stage circuit and it is considered how to translate the technique into measurements.**

I. Introduction

The design of filters for given limit values in the frequency domain is well known in signal processing tasks. However, the procedures are not directly assignable to reduce conducted emissions with line filters due to the four port behavior of the filter structures. To overcome the widely used trial- and error method, it is necessary to choose the filter elements in respect to the mainly disturbing noise source mode as shown in [1] and [2]. The occurring noise voltages are decoupled into common- and differential-mode disturbances with the help of 0° and 180° power-combiners. Only if the dominant noise mode is damped, the line voltages can be reduced to reach the given limit values. However, the method is only valid for symmetric filter structures due to the well known common- and differential-mode equivalent circuits can not cope with occurring mode conversions e.g. common- to differential-mode [1]. However, a lot of non symmetric structures are in use like a simple inductive filter or the widely used Π-structures. Thus, a full mathematical description of the device under test (DUT) is necessary, as shown in section II.

Figure 1 shows the general measurement and simulation setup to receive the conducted noise voltages on both power lines. The noise currents, generated by the DUT, are decoupled with the LISN (line impedance stabilization network) and applied to a measurement receiver or spectrum analyzer. The setup described in figure 1 concerns to the setup described through the CISPR25 [3] regulatory standard, but can also be translated to the CE or FCC setup. The DUT contains the application or functional part as well as the considered line filter, which is improved until the given limit values for conducted emissions are reached. The elements of the line filter are chosen in respect to the maximum functional current, desired attenuation and the available space within the housing.

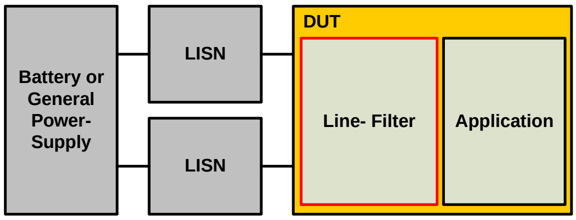

Fig. 1 General measurement / simulation setup for conducted emissions

A functional network simulation of the whole system can estimate the filter attenuation. In many cases power stages or in general assemblies with non-linear elements are considered. Thus, only a transient simulation will replicate the noise spectrum of the application and is capable to rate the filter attenuation. However, the simulation time can rise up to several hours of calculation to reach a steady state condition, especially if high inductive line filters are used.

To overcome this problem, chapter II introduces the matrix source description within the time domain in respect to Thevenin's and Norton's theorem. Data are transferred into the frequency domain by applying a fast Fourier transform. The "noise" system can be considered as linear, as long as the following filter elements do not have an effect to the switching behavior and function of the elements. This assumption should be always valid during the filter development process; otherwise the filter element belongs to the functional part of the DUT.

The DUT without filter has to be described only once in the frequency domain. Thus, following filter simulations can be carried out within the frequency domain much faster than within a transient simulation of the whole system.

Figure 2 shows all needed parts of the system, described through impedance [Z] or admittance [Y] matrices. The DUT and the *Supply+LISN* parts are described as a two port [2x2] matrix. Due to the four port behavior of the filter, a [4x4] [Z] or [Y] matrix is necessary.

Within the measurement and the simulation the *Supply+LISN* part is always present and has to be de-embedded as shown in chapter III, before the whole system, including the filter element, can be built up as matrix system.

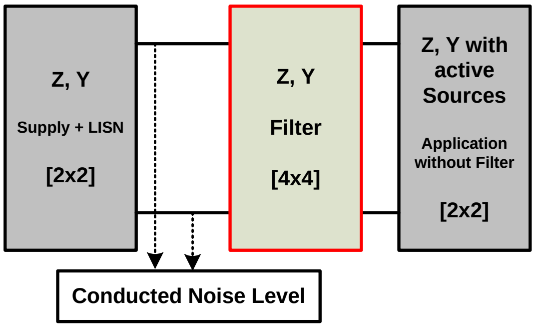

Fig. 2 Matrix description of the whole system

If all parts of the system are characterized, the conducted noise level can be easily calculated. Especially if different filter elements are available as a library, the embedded filter attenuation can be calculated within seconds.

Chapter IV presents the method for a simulation of a full bridge motor drive, whereas chapter V tries to describe the method for measurement setups.

Not every filter structure can be calculated with impedance or admittance matrices. Thus, the method is limited to the numerical stability of ill-conditioned matrices as summarized in chapter VI.

II. Active Source Description

The source description bases on Thevenin's law which describes, that every arbitrary unknown circuitry with active sources can be described with a passive impedance matrix and additional active sources [4]. Thevenin's law is equivalent to the Norton theorem, using the port current values.

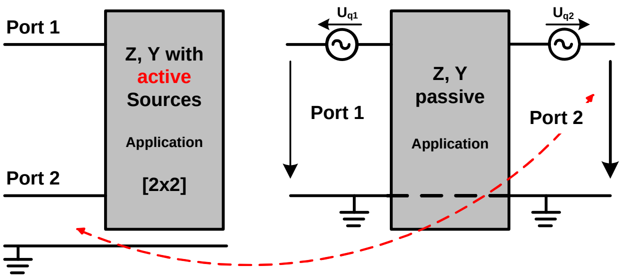

Fig. 3 Translation from the classic DUT description to a passive matrix with active sources in respect to Thevenin's law

Figure 3 displays the translation from the general or classic DUT description to the well known two port description with active sources and included reference ground. Port voltages are described as

$$\begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \times \begin{pmatrix} i_1 \\ i_2 \end{pmatrix} + \begin{pmatrix} u_{q1} \\ u_{q2} \end{pmatrix} \qquad (1)$$

with the impedance matrix elements z_{xx}, port current values i_x and the open circuit voltages u_{qx}.

Equation 1 consists of 6 complex parameters. The parameters have to be evaluated through three independent measurements / simulations. The first measurement evaluates the open circuit voltages $u_{q1}(t)$ and $u_{q2}(t)$ whereas measurement two and three apply a defined load impedance Z_e to the DUT ports.

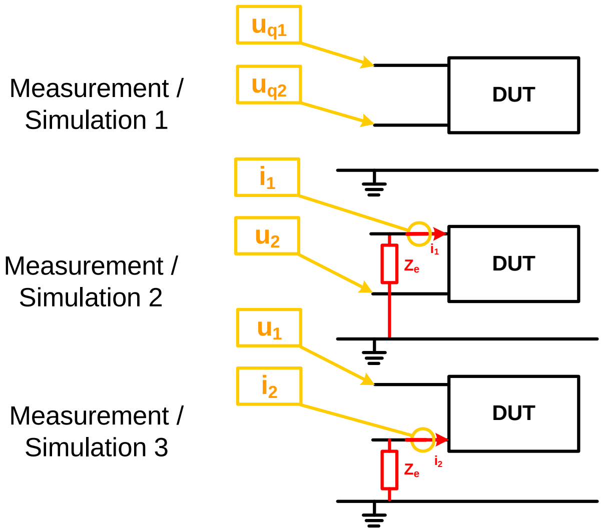

Fig. 3 Measurement steps to define the matrix parameters

Z_e is chosen as a 50 Ω termination resistor. After all voltage and current data are available, the values are translated into the frequency domain with the help of the FFT. Care should be taken that the transient simulation is within a steady state condition and start up sequences are not within the considered interval. Measurement data have to be within the dynamic range of the oscilloscope and the trigger position should be kept constant at the same channel and amplitude for all three measurements.

If the data are available within the frequency domain, the parameters of the passive source matrix can be calculated as:

$$Z_m = \begin{bmatrix} -\frac{u_{q1}}{i_1} - Z_e & \frac{u_1 - u_{q1}}{i_2} \\ \frac{u_2 - u_{q2}}{i_1} & -\frac{u_{q2}}{i_2} - Z_e \end{bmatrix} \qquad (2)$$

The impedance matrix [$\underline{Z}_m$] is represented through four complex parameters representing each a frequency array with the resolution defined during the FFT.

III. De-embedding of the Stabilisation Network

Whilst the parameter extraction in chapter II, the DUT has to be power supplied with the help of the stabilization networks. Even the LISN consists of very high inductive coils, the impedance can influence the measured matrix [$\underline{Z}_m$] within the lower kHz range. The calculated impedance matrix [$\underline{Z}_m$]

and the open circuit voltage vector $[\underline{u}_q]$ can be translated into admittance values $[\underline{Y}_m]$ with parallel current sources $[\underline{i}_q]$ as shown in equation (3) and (4).

$$Z_m = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \Rightarrow Y_m = \begin{bmatrix} \frac{Z_{22}}{|Z_m|} & -\frac{Z_{12}}{|Z_m|} \\ -\frac{Z_{21}}{|Z_m|} & \frac{Z_{11}}{|Z_m|} \end{bmatrix} \qquad (3)$$

$$u_q = \begin{bmatrix} u_{q1} \\ u_{q2} \end{bmatrix} \Rightarrow i_q = \begin{bmatrix} -\frac{Z_{22}}{|Z_m|} u_{q1} + \frac{Z_{12}}{|Z_m|} u_{q2} \\ \frac{Z_{21}}{|Z_m|} u_{q1} - \frac{Z_{11}}{|Z_m|} u_{q2} \end{bmatrix} \qquad (4)$$

The application together with the supply circuit can be seen as a parallel connection of two admittance matrices as shown in figure 4.

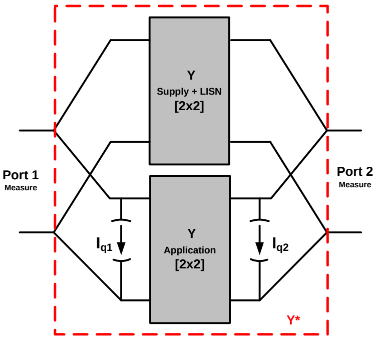

Fig. 4 Paralleled admittance matrices of the application and the stabilization circuit

The admittance matrix of the stabilization circuit *Supply+LISN* is calculated with a network simulation or measured with a vector network analyzer (VNA) as $[\underline{Y}_{LISN}]$ and subtracted of the measured admittance matrix $[\underline{Y}_m]$. The requested application matrix is thus given as

$$[\underline{Y}_{DUT}] = [\underline{Y}_m] - [\underline{Y}_{LISN}] \qquad (5)$$

whereas the current vector $[\underline{i}_q]$ is not changed due to the LISN circuit does not provide additional high frequency currents. With the DUT, the filter and the stabilization network all parts of the system are available as admittance or impedance matrices, it is possible to calculate the requested noise voltages at the output of the filter circuit. The whole calculation would go far beyond the scope of this paper - however, one has to use the boundary conditions of two serialized impedance matrices for example to calculate the requested voltages.

IV. Example with a Full Bridge Motor Drive Simulation

As an example, a power stage to drive an inductive load e.g. an electric motor drive, is simulated within a network simulation. The simulation includes the power stage, the control unit, the intermediate circuit with bulk capacitors, the considered filter element and the stabilization networks to decouple the noise currents as shown in figure 5. Parasitic capacitors are also included to simulate occurring common-mode currents which return path is represented through the reference ground plane. Depending on how detailed the parasitic elements are chosen, one simulation can take up to 20 minutes of calculation time to reach the steady state condition within a transient simulation.

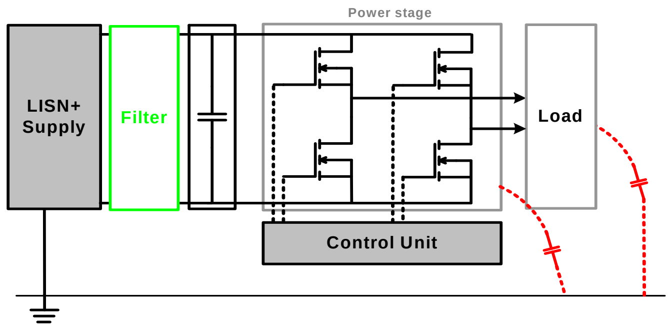

Fig. 5 Simulation setup for a full bridge motor drive

To characterize the DUT, three simulations are carried out and the parameters as described in equation (2) are evaluated. Within the next step, the LISN or supply circuit is de-embedded with the LISN admittance matrix. As the noise source is characterized, the desired filter circuit has to be evaluated within the frequency domain to receive the [4x4] filter impedance matrix.

A widely used filter structure as shown in figure 6 is considered to damp the occurring conducted noise current. The impedance matrix is automatically calculated within a separate network simulation and committed to the post process, combining the individual systems and calculating the resulting noise voltages with filter element.

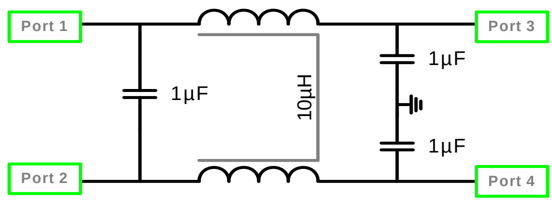

Fig. 6 Filter segment

The filter elements are considered as real elements with ESL and ESR (equivalent series inductance/resistance) and a non perfect coupling between the coils of the common-mode choke. A control simulation with filter element in respect to figure 5 is carried out to show that the noise voltage is calculated correctly. Figure 7 shows the calculated noise voltage compared with the control value. Displayed is the noise voltage of the battery plus line above a 50 Ω resistor. The frequency range is considered up to 108 MHz for automotive purposes whereas FCC or CE applications only consider frequencies up to 30 MHz. As can be seen, the calculated and simulated values for the noise voltage match over the whole frequency range.

However, the noise floor voltage can not be calculated due to the missing original data at these frequency points. Only if the frequency spectrum of the driving voltage is higher than the noise floor i.e. existing, the impedance matrix can be calculated with a prediction of the noise voltage for different filter elements. The filter elements can now be replaced by different filter topologies without the need of recalculating the whole model.

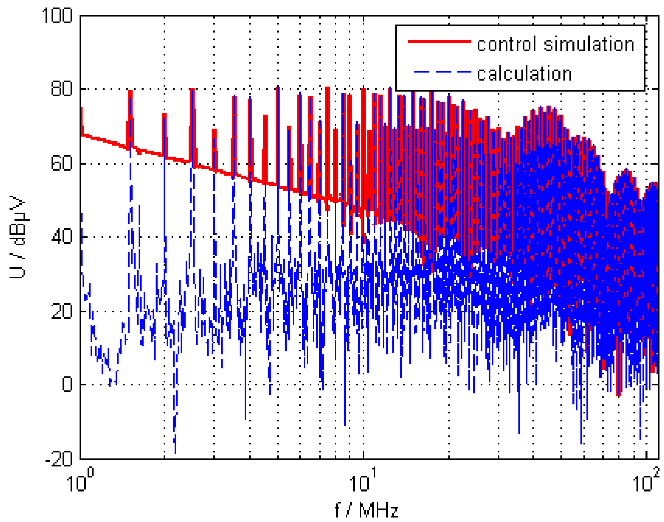

Fig. 7 Calculated noise voltage with used filter element compared to the control simulation

As mentioned above, the limiting factor is given through the steady state condition of the simulation circuit. If the simulation is stopped too early or the start up condition is used to calculate the frequency spectrum, wrong values are calculated for $[\underline{u}_q]$ and the impedance matrix $[\underline{Z}_M]$.

V. Measurement Experience

The method is completely transferable to the measurement setup. However, it is recommended to build up the stabilization networks as well as the ports for the defined load impedances on one common printed circuit board. The ports for the defined load impedances can be build up with SMA plugs which allow to connect single 50 Ω terminations as Z_e impedance. The impedance matrix of the LISN $[\underline{Y}_{LISN}]$ can be evaluated through a two port VNA measurement. The three measurements as described in figure 3 are carried out with special care in respect to the same trigger time and amplitude for all measurements. Otherwise a time shift would result as a phase shift after the following FFT. The current values within the measurement steps two and three are calculated out of the voltage drop above the load resistor Z_e. After all needed parameters are available, the impedance matrix can be used as shown in chapter IV. Averaging of the acquired data within the time domain helps to improve the dynamic range within the frequency domain.

VI. Lmits

The method is limited to problems which are numerically well-conditioned. For example, a simple X-capacitor filter without shunt resistors is not defined for the impedance matrix $[\underline{Z}]$. Only with used shunt resistors, the matrix is defined, however may be ill-conditioned. Another problem arises if very high impedance values are used, e.g. for idealized systems without coupling of the DUT to the ground system.

Another limit is given as only periodic noise producing systems can be evaluated. Random signals like data transmission lines with simulated or measured data flow can not be considered due to the frequency spectrum is changing over different time intervals.

The method should work well as long as the filter is not influencing the function of the DUT or changing any switching behavior. In this case, the noise sources within the frequency range can be threat as linear system.

VII. Conclusions

Characterizing artificial applications with the help of a passive admittance or impedance matrix and two active sources can help to speed up the simulation time for the filter development process enormously. Once the DUT's matrices are characterized, no more time intensive transient simulations have to be carried out. The filter attenuation can thus be calculated easily within the frequency domain for any kind of filter structure. Especially if a filter library, characterized as $[\underline{Z}]$ or $[\underline{Y}]$ matrices, is available, the behavior of the filter together with the DUT can be analyzed quickly. The method however is limited to problems with periodical noise sources which generate a constant and reproducible noise spectrum over the considered time interval.

References

[1] H. M. Rebholz and S. Tenbohlen, "Prospects an limits of common- and differential-mode separation for the filter development process," EMC Europe 2008, 8th – 12th September 2008, Hamburg, Germany

[2] C. R. Paul, Introduction to EMC, New York, Wiley & Sons, Inc., 1992, p. 466 – 474

[3] CISPR 25, "Radio disturbance characteristics for the protection of receivers used on board vehicles, boats, and on devices – Limits and methods of measurement," August 2002, International Electrotechnical Commission.

[4] M. F. Moad, "On Thevenin's and Norton's equivalent circuits," Education, IEEE Transactions on Education, Vol. 25, August 1982, p. 99 - 102