Multi-Channel Time-Domain EMI Evaluation of Dominant Mode Interference for Optimized Filter Design in Three-Phase Systems

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Abstract—This paper describes optimal three-phase filter design based on the measured dominant mode of interference. The modes of interference are determined by simultaneously measuring currents and voltages in all phases in time domain, using a multi-channel digitizer. The measured results are evaluated in frequency domain after fast Fourier transform. While usual electromagnetic compatibility measurement equipment is evaluating only one single channel, the described multi-channel technique allows rapid estimation of dominant modes, for stationary loads, but also for cyclo-stationary, transient and nonlinear loads. Using this method, the topology of power line filter for sufficient suppression of a specific mode of interference from commercial of the shelf three-phase power converter is estimated.

I. INTRODUCTION

One of the major sources of electromagnetic interference (EMI) are switched mode power supply (SMPS). Often, commercial of the shelf (COTS) power supplies are used in many industries, including power defense electronics. These COTS power supplies are specified and tested according to the basic civil electromagnetic compatibility (EMC) standards, which start at only 150 kHz. Although, the interest for the 10 kHz-150 kHz range is growing [1], most COTS equipment fail the requirements below 150 kHz [2], [3]. COTS SMPS with interference below 150 kHz which had to comply with the military standard for conducted emission were investigated in this paper. To comply with standards for professional applications, an external power line filter (PLF) should be implemented. The design and performance of a PLF strongly depend on the terminating impedances on both sides of the filter. Ignoring these parameters on the design stage can lead to oversized and costly filters. Moreover, under certain conditions filters with a poor design may even amplify the noise [4].

Components that define the common mode (CM) noise source impedance are the unintentional capacitance between the switching device and the heat sink, parasitic capacitance between the heat sink and the grounded chassis, and parasitic capacitance between other parts of the setup, which carry pulsating current, and the grounded chassis; components that define the differential mode (DM) noise source impedance is the turned-on resistance of the rectifying diodes, the equivalent series resistance and the equivalent series inductance of the bulk capacitor [5]. At lower frequencies (below 1 MHz), interference is mainly DM while at higher frequencies it is mainly CM [6] because parasitic effects create a low-impedance pass for interference. Ideally, each mode of noise is suppressed by the respective section of the filter [7]. A typical generic filter topology of a power supply filter is composed of a common mode choke (CMC), a line inductor (DM choke), X-capacitors (e.g. capacitors connected between lines for DM attenuation) and Y-capacitors (e.g. capacitors between lines and ground for CM attenuation) [8]. Despite the ubiquitous use of these components, there are some drawbacks that designers and users of the filters should be aware of. DM chokes or line inductors are usually bulky, so for systems that require compact dimensions, those are not suitable. Furthermore, $C_x$ capacitors have a limited lifetime because of the reactive current. There are several typical topologies of PLF based on basic filtering circuits. With increasing filter order, the insertion loss (IL) increases with 20 dB/dec. This ideal IL rate can only be achieved if the terminated impedances on both ends of the filter are appropriate [9]. To give sufficient attenuation, an inductor that faces the input of the SMPS should have a much higher impedance than the noise source impedance (Fig. 1,a). If the capacitor faces the input of SMPS (Fig. 1,b), a capacitor’s impedance should be much lower than the noise source impedance [4]. COTS SMPS are designed to fulfil EMI requirements from 150 kHz, while many system integrators are faced with EMI requirements starting at 10 kHz. In short, this means more than 10 times bigger inductors and/or capacitors to achieve the required IL, which is a major challenge (and fight with mechanical engineers for the required volume). Thus, knowing the noise source and the load impedances, we can design a perfect filter for each particular case. Various approaches for in-situ impedance measurements were devel-
oped previously [5], [9]–[12]. However, all of the proposed approaches are time-consuming, due to the pre-measurement calibration process and require expensive equipment which is not always available. Furthermore, those approaches are not suitable for three-phase systems. For these reasons a trial and error method for designing and implementing a PLF is still the most used approach in the industry. As a result, overdesigned and expensive filters are implemented in systems and this becomes annoying when space and costs are an issue. These are the main reasons for developing a simplified approach for designing and implementing suitable filters for three-phase systems. It should be noted that the conventional method of measuring the interference in the industry uses a one or two-channel EMI receiver which requires a significant amount of time per test. Also, usually only the voltage is considered.

This paper proposes a method based on multi-channel time-domain measurements of the current, which allows us to determine the dominant mode of emission and find a suitable configuration of the filter. The aim of the paper is to create an approach convenient for industrial applications.

II. THEORETICAL APPROACH FOR A 3-PHASE SYSTEM

A. Proposed method

In order to optimize the filter design without measuring the impedances of the system, analysis based on the dominant mode of interference can be made. Whereas, the total interference is the sum of DM and CM interference, the most efficient way to reduce the total interference is to apply a filter for suppressing the dominant mode of interference. To determine the dominant mode of interference without using a noise separator the current measurement should be performed. DM and CM current for a single line can be obtained according to Eq. 1 and Eq. 2 by measuring the line currents in three-phase systems [13].

\[
\begin{align*}
    i_{CM} &= \frac{i_u + i_v + i_w}{3} = \frac{i_{gnd}}{3} \\
    i_{DM} &= i_u - i_{CM}
\end{align*}
\]

Then, determining the dominant mode of emission is possible by comparing DM and CM currents. Thus, the topology of the filter for the efficient suppression of interference can be chosen with the flow-chart shown on Fig. 2. Use of the multi-channel oscilloscope allows to measure each phase current (e.g. normal mode), all phase currents together (e.g. common mode) and line voltages simultaneously. That reduces measurement and post-processing time. The block diagram of the measurement setup representing the proposed approach can be seen in Fig. 3. Setup with three separate line impedance stabilisation network (LISN) is used to measure all line voltages simultaneously. With current clamps measuring current flowing in three separate lines simultaneously the CM current is obtained. By measuring current flowing in all lines together we obtain the normal mode (NM) current, that is used to calculate DM current. Then the analysis in terms of the dominant mode of the interference can be made.

III. TEST CASE

The voltage measured with a conventional EMI receiver from the output of the LISN of a three-phase 6 kW 380/480 V AC to 52/48 V DC converter is shown in Fig. 4. Even with an internal input filter, this converter does not comply with AECTP 500 NCE02-1 [14]. Hence, an additional PLF is required.

![Fig. 2: Approach flow chart.](image)

![Fig. 3: Block diagram of the measurement setup.](image)

![Fig. 4: Conducted emission from SMPS.](image)

The schematic of the filter which was used initially can be seen in Fig. 6. Fig. 5 shows the IL for Common, Differential and Normal Modes provided in the datasheet from which we can see that the filter has an attenuation over 100 dB in a broad frequency range (approx. 200 kHz – 1 MHz), while the significant emission from the SMPS is present only at 100 kHz [15]. Furthermore, the information given in the datasheet is
relevant for a situation where the impedance is matched, i.e. when the noise source impedance and network impedance are equal to 50 Ω. As predicted, in the real system, when the noise source and the load impedances are not known and not equal, the filter shows significantly lower attenuation (Fig. 7). All measurements hereafter are performed using the time-domain measurements, and converted to frequency domain using fast Fourier transform (FFT). Also, it should be noted that in this set up the effective attenuation is only provided at the frequency range of 10 kHz – 200 kHz, since there is no interference to suppress at higher frequencies.

To design a suitable filter for this particular case, measurements of the CM and NM currents were performed using the Picoscope TA189 current clamps and calculated according to Eq. 1 and Eq. 2. The measurement setup is shown in Fig. 8. Three one-phase LISN are used to provide a reliable impedance and to allow simultaneous measurements of the three line voltages. The 8-channel Picoscope is used instead of an EMI receiver, which allows us to observe the three line voltages and CM and DM currents simultaneously. This significantly reduces the measurement time needed.

V. RESULTS

Comparing the current spectrums shown in Fig. 9 the conclusion is made that the DM is the dominant mode of emission of the device under test (DUT). This is, as expected for a low frequency, due to the nature of the DM noise propagation, as discussed in the introduction. Further measurements were performed with inserted \( C_x \) capacitors or line inductor or a combination of those (Fig. 10). First, a 1.5 mH inductor is inserted and then a 40 \( \mu \)F capacitor, which is a first order filter.

The inductor provided 5 dB higher attenuation than the capacitor on the frequency of interest, which allows us to make an assumption that the noise source impedance can be considered as ‘low’. To confirm this, a second-order topology filter was created using the previously selected components. Two configurations of filter circuits consisted of the same components were tested: LC and CL. The results can be seen in Fig. 11 and Fig. 12. The attenuation in total is improved when compared to inserting only one of these components, but a noticeable difference can be seen in performance by changing the LC configuration into CL. It shows that CL configuration gives a better attenuation than an LC configuration. As can be seen the CL configuration of the second-order filter topology is outperforming the initially used COTS PLF. According to [9] this confirms that the noise source impedance is...
can be considered as low and for the effective attenuation the inductor should face the input of the SMPS.

![Fig. 10: Voltage with first order filter topology.](image)

![Fig. 11: Voltage with second-order filter topology (LC combination).](image)

![Fig. 12: Voltage with second-order filter topology (CL combination).](image)

**VI. Conclusions**

A simple and time-efficient approach for filter design in three-phase systems is proposed using a low-cost multi-channel digital oscilloscope which allows performing more efficient testing compared to a conventional EMI receiver. By measuring the CM and DM currents, the dominant mode of interference of DUT can be assessed. Following the proposed approach this will result in the selection of most useful suppression components, much better than the conventional method of applying COTS filters that often employ several useless but costly and bulky components. Based on the noise source impedance a suitable topology of the PLF can be determined, however as was shown in this paper the impedance can be estimated by inserting different component types with several values. The total interference from SMPS is suppressed sufficiently by implementing a second-order filter with a specific orientation, as only in CL configuration the suppression is sufficient by implementing a second-order filter with a specific topology.

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