# An EMC evaluation of the use of unshielded motor cables in AC adjustable speed drive applications

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***Abstract*— The most common solution for modern adjustable speed drives (ASD) is the use of induction motors (IM) fed by voltage-source inverters (VSI). The inverter generates a pulsewidth modulated (PWM) voltage, with *dv/dt* values of about 6 kV/$\mu$s or even more. In three-leg inverters for three-phase applications the occurrence of common-mode voltage is inherent due to asymmetrical output pulses. As a result, for electromagnetic compatibility (EMC) reasons, in most applications shielded cables are used between the inverter and the motor, implying high installation costs. The present paper discusses the use of cheaper, unshielded cables. A new method for measuring electromagnetic interference (EMI) from unshielded cables is proposed and measurement results are presented. The level of EMI is evaluated in different situations: without an output filter, with a classical LC output filter and with an advanced output filter with DC link connection. It is concluded that, from an EMC point of view, unshielded cables can give very good performance provided that a common-mode (CM) output filter is used.**

## I. Introduction

The standard solution used in industry for AC adjustable speed drives (ASD) remains the PWM voltage source inverter (VSI) but a lot of research is done on alternative topologies [1], [2], [3]. The VSI presents many advantages: high efficiency (up to 98%), open-circuit protection, small relative size, excellent regulation capabilities, wide speed range, constant high input power factor, common bus regeneration and others. To achieve high efficiency levels, fast switching IGBTs are used. As a consequence, at the output of the VSI, PWM pulses with high *dv/dt* (6 kV/$\mu$s or higher) will be present. In a three-phase inverter, PWM also generates common-mode (CM) voltage because of asymmetrical voltage pulses. In Fig. 1 a switching pattern is shown, and it can be observed how the CM voltage is generated. This voltage is obtained by adding the three voltages resulting from the three inverter legs like this:

$$V_{cm} = \frac{V_a + V_b + V_c}{3} \qquad (1)$$

Having the DC-link mid-point as a reference, the voltages $V_a$, $V_b$ and $V_c$ can either be +$V_{dc}$ /2 or –$V_{dc}$/2, where $V_{dc}$ is the DC-link voltage. As a result, depending on the state of the switches, the common mode voltage can take one of the values $\pm V_{dc}$/2 (when all three legs are connected simultaneously to either the positive or the negative bus rail) and $\pm V_{dc}$/6 (when two legs are connected to one bus rail and the third one is connected to the opposite rail). As a consequence, a usual three-leg inverter can not have an output CM voltage equal to zero, and this voltage is bigger ($\pm V_{dc}$/2) if the zero vector is employed (all three legs in the same switching state).

CM voltage with high *dv/dt* in the cable between the inverter and the motor is a potential source of EMI, therefore usually shielded motor cables are used. Such cables are expensive and increase the overall installation cost. Unshielded cables are much cheaper but their use is restricted by EMC related concerns. A complete investigation from EMC point of view about the use of unshielded motor cables is not known to be presented in literature until now although the issue of motor cables for ASD applications has been discussed in papers such as [4]. Following, a new method for measuring conducted CM noise on unshielded motor cables will be proposed. This method will be further used for evaluating the EMI in the case of an inverter without output filter and the effect of two different output filter topologies: a classical LC filter (Fig. 2(a)) and a more advanced filter with DC link connection (Fig. 2(b)).

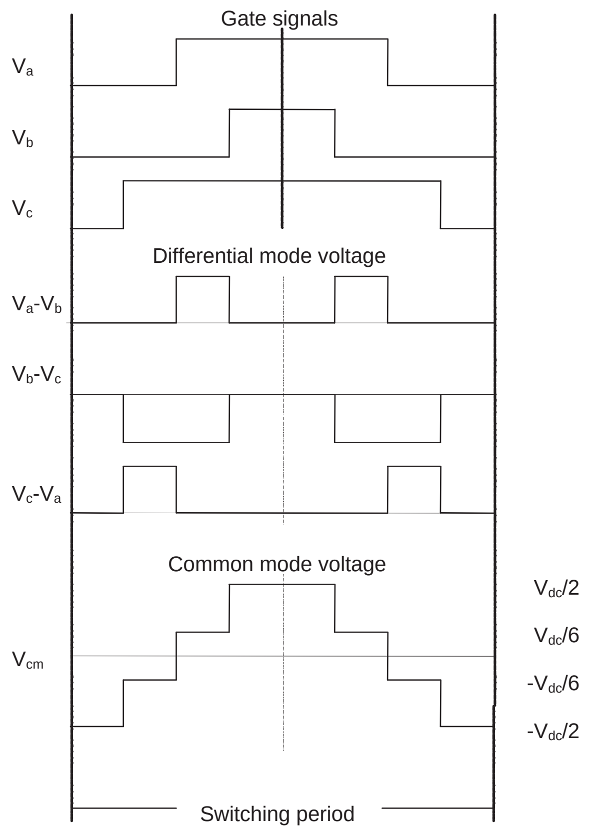
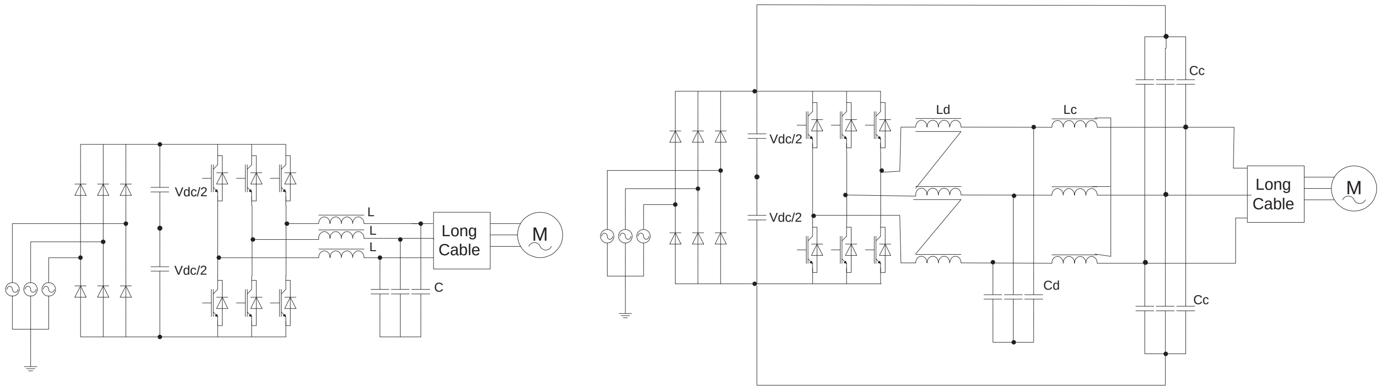



Fig. 1. Common-mode voltage generation in a PWM inverter




(a) LC Filter (b) Filter with DC link feedback

Fig. 2. Investigated output filter topologies

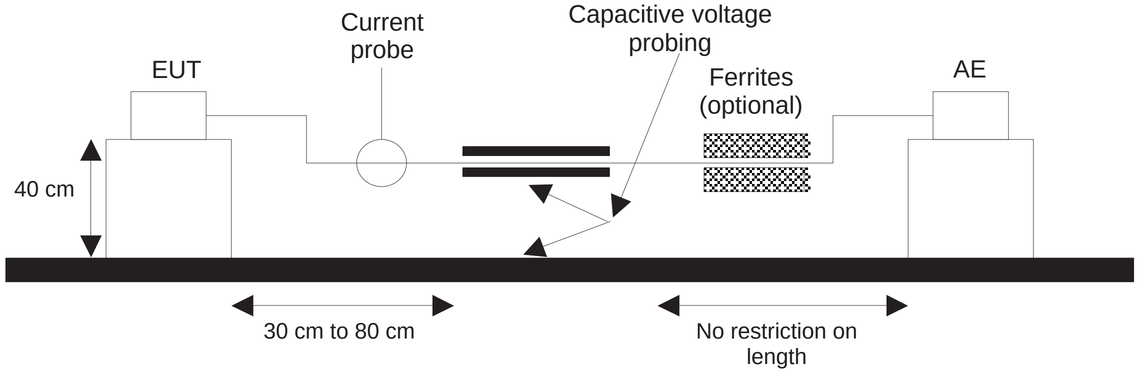



Fig. 3. Set-up C.1.3. for measuring CM noise on unshielded cables, described in CISPR 22 [6].

## II. Conducted CM noise measurement on unshielded motor cables

The measurement of conducted CM noise in the cable between the inverter and the motor is not an easy task, especially because of the high levels of CM voltage at the switching frequency (practically the peak-to-peak value of the CM voltage is $V_{dc}$) and the steep voltage pulses. The use of a Line Impedance Stabilization Network (LISN) on the output of the inverter is obviously excluded because of the above-stated reasons. Consequently, a non-intrusive method has to be used. Previous work [5] confirmed the possibility of using a set-up from the CISPR 22/EN55022 [6] standard for measuring conducted CM noise on shielded motor cables. Even if CISPR 22 is not a standard for electric drives, but for IT equipment, the ”in situ CDN/ISN” configuration was proved to be usable for measuring CM noise produced by an ASD when a shielded cable is used.

Further, another non-intrusive method was searched and, considering previous experience and opinions of other scientists, it was decided to test the configuration C.1.3 from CISPR 22, the combination of current probe and capacitive voltage probe (Fig. 3) for measurements on unshielded cables. In this case EUT is the ASD and AE is the induction motor. The configuration C.1.3 from CISPR 22 requires both voltage and current measurements. This requirement is a consequence of the unknown common-mode impedance of the auxiliary equipment. The particularity of this measuring method is the lack of a well defined CM impedance, unlike other set-ups that require a 150 Ω CM impedance. The high CM voltage levels due to the three-phase PWM pulse pattern and high *dv/dt* make the use of a well-defined CM impedance impractical. In order to comply with the standard, both current and voltage limits have to be met.

A first attempt to build the capacitive voltage probe was to wrap an aluminium foil around the unshielded cable, on the length of 55 cm. The standard requires a minimum length of 50 cm. The aluminium foil was fixed with copper tape, and a tap was made at the middle of the clamp, also using copper tape. An insulator keeps the cable at a constant distance from the ground plane (10 cm). The cable length used was 5 m for practical reasons, in order to keep the cable straight over the ground-plane. The whole set-up was installed in a shielded room, to avoid interference from external fields.

The CM voltage was picked up between the tap and the ground plane. For visualizing the voltage a high-impedance probe (10 MΩ) and a digital oscilloscope were used. The digital oscilloscope was also used for data acquisition for further processing (FFT analysis).

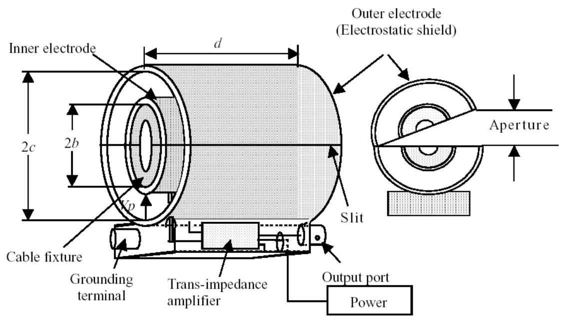



Fig. 4. Construction of the capacitive voltage probe [10].

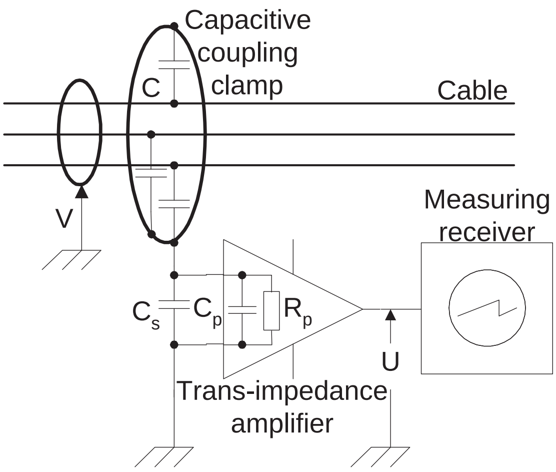



Fig. 5. Measurement circuit with the capacitive voltage probe.

For noise measurements a spectrum analyser was connected to the capacitive clamp with a standard voltage probe, as described in CISPR 16 [7]. However, because of the low impedance of the voltage probe (1500 Ω), this probe could be used only for measurements above 1 MHz, where the impedance of the capacitive voltage clamp becomes lower than the impedance of the voltage probe. For frequencies below 1 MHz the only way of observing the spectrum of the CM voltage noise is to perform a FFT analysis of the voltage acquired with the digital oscilloscope.

The method used for building the capacitive clamp presented above has several shortages: low immunity to external fields, the capacitance of the probe is not well defined since both the length of the probe and the diameter of the cable can vary from one test to another. Several papers [8], [9] as well as work within standardization groups suggest the use of a more advanced voltage probe which meanwhile is also commercially available. This high-impedance voltage probe consists of two electrodes, one inner electrode for picking up the signal from the cable and the other one for shielding the first electrode from external electric fields. The signal from the capacitive clamp is applied to a trans-impedance amplifier, situated in the immediate vicinity of the clamp. The construction of such a capacitive voltage probe is shown in Fig. 4 [10]. The voltage division depends on the type of cable and it still requires separate calibration for each cable type. Considering the circuit in Fig. 5 the voltage division factor is given by:

$$F_a = \frac{V}{U} = \frac{C_p + C_s + C}{C} \cdot \frac{1}{G_p} \qquad (2)$$

where $F_a$ is the voltage division factor, $V$ is the common-mode voltage, $U$ is the measured voltage, $C$ is the capacitance of the capacitive clamp, $C_p$ is the internal capacitance of the trans-impedance amplifier, $C_s$ is the capacitance between probe and ground and $G_p$ is the gain of the trans-impedance amplifier. Unfortunately the commercially available capacitive voltage probe can not measure voltage levels as high as the common-mode voltage produced by a PWM inverter, therefore this probe has been used only when experimenting with common-mode output filters.

With the capacitive voltage probe tests were also made with a 100 m unshielded motor cable. The cable was coiled for practical reasons and the tests were done in different situations: cable at different heights over the ground plane, cable coil on the ground plane and cable coil on the ground plane wrapped in aluminium.

For the current measurement, a standard high frequency current probe was used. The measurement of the CM current does not pose any special problems, as the value of the CM current is relatively low.

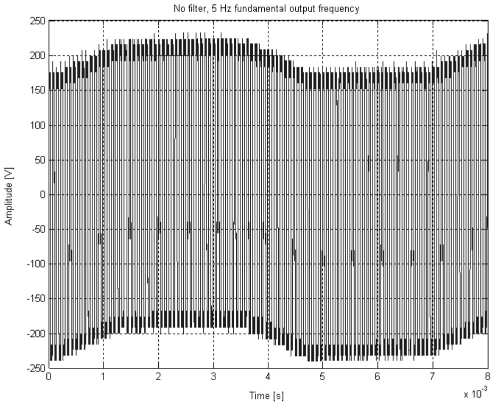
## III. Measurement results

Two sets of experiments were conducted. A first set of experiments aimed the evaluation of CM noise on the motor cable when no output filter is used and when the investigated output filters are used. For this purpose the CM voltage was measured with the first method, namely the aluminium foil wrapped around the unshielded cable. The second set of experiments focused on the use of the filter with DC link feedback which is very effective both in DM and CM. The aim of this second set of tests was to evaluate, as accurately as possible, whether unshielded motor cables can be used or not without causing EMI. A commercial capacitive voltage probe was used for these experiments.

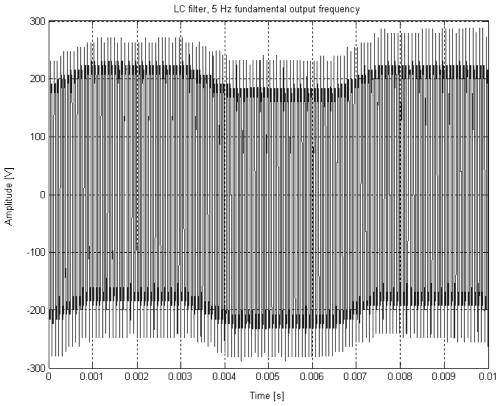
For the tests a 3 kW induction motor at 400 V was fed by a 3 kW commercial ASD, running with 13 kHz switching frequency and 5 Hz fundamental output frequency. A low output frequency, and consequently a low output voltage, was used because it is considered a worst-case situation for the CM voltage generation. In this situation the "zero" switching vector that produces the highest CM voltage occurs for a longer period than at higher output frequencies.

### A. Experimental results with a short motor cable

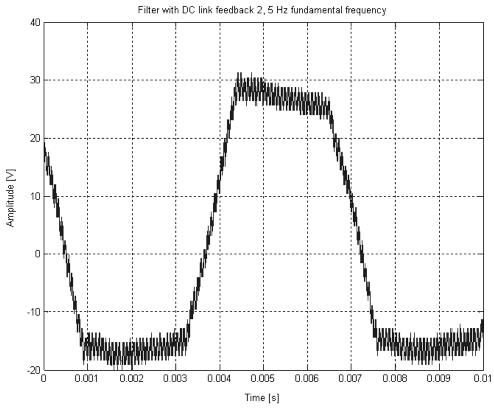
The first set of experiments was conducted using a 5 m unshielded motor cable. The CM voltage was measured using a capacitive clamp built using aluminium foil wrapped around the unshielded cable. Fig. 6(a) shows the CM voltage measured on the capacitive clamp. The peak-to-peak voltage is very high, over 400 V. The FFT of this voltage (up to 1 MHz) in Fig. 7(a) shows a very noisy spectrum, with high-amplitude harmonics of the switching frequency. Between 1 MHz and 30 MHz, measured with the spectrum analyser having a resolution bandwidth (RBW) of 1 kHz and peak detector, the CM voltage




(a) No filter

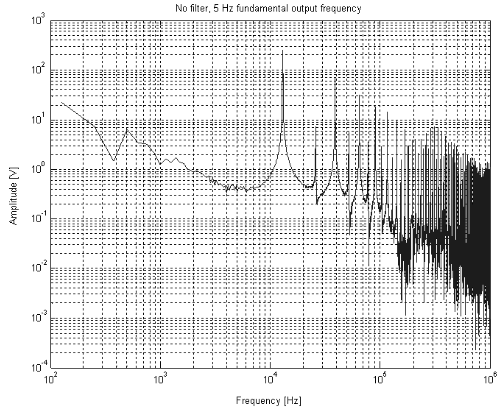



(b) LC filter

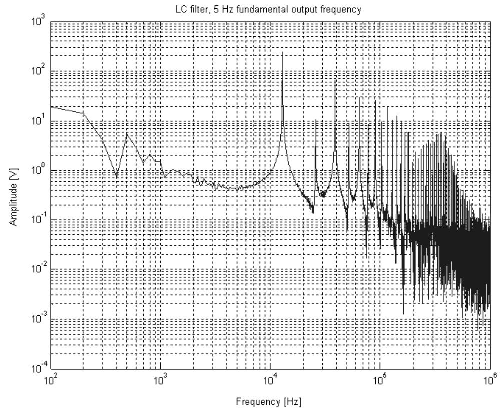



(c) Filter with DC link connection

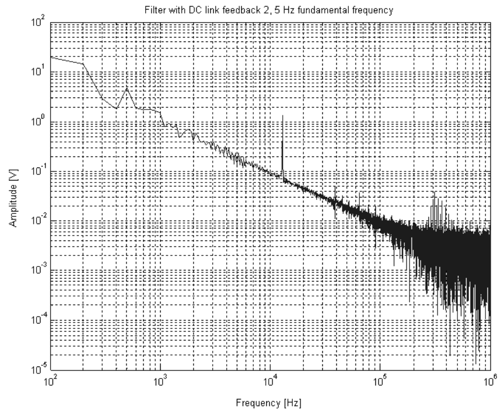
Fig. 6. Voltage on the capacitive clamp.




(a) No filter




(b) LC filter



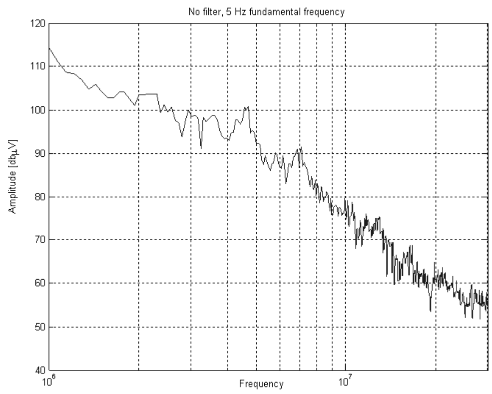

(c) Filter with DC link connection

Fig. 7. FFT of the voltage on the capacitive clamp.

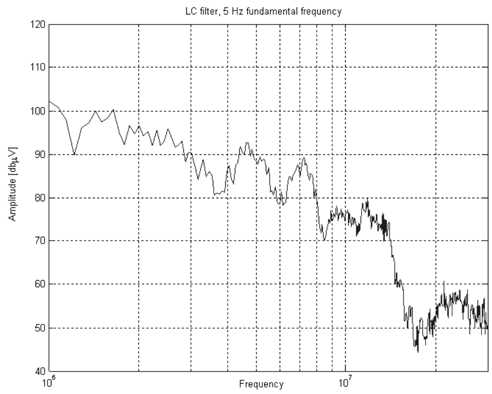
is still very noisy. This is shown in Fig. 8(a). In many applications these levels would be prohibitively high.

Two different output filters have been fitted at the inverter output (Fig. 2) to reduce the noise level. The first one, shown in Fig. 2(a), is a classical LC filter. It consists of differential-mode (DM) inductors and DM capacitors (also known as ”X-caps”). The second filter shown in Fig. 2(b) consists of a classical DM filter followed by a CM inductor and CM capacitors (also known as ”Y-caps”) connected to the DC link + and – rails. Both filters were commercial equipments and a comparison was needed because of reported claims that the LC filter would improve EMI performance and allow the use of unshielded cables.

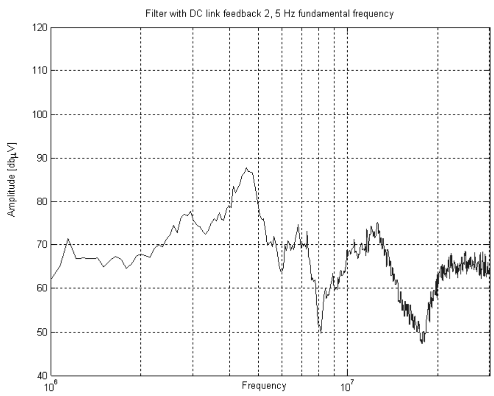
With the LC filter installed the CM voltage (Fig. 6(b)) has the same high peak-to-peak value of over 400 V, as in the situation without filter. In the FFT of the CM voltage (Fig. 7(b)) again no significant improvement can be observed. In the 1 MHz - 30 MHz range the noise is reduced, but it still has a very high level (Fig. 8(b)). The filter with DC link connection, due to its CM attenuation, drastically reduces the CM voltage




(a) No filter

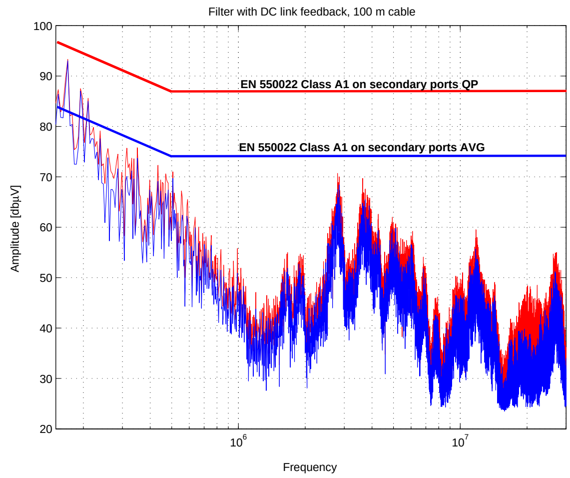



(b) LC filter

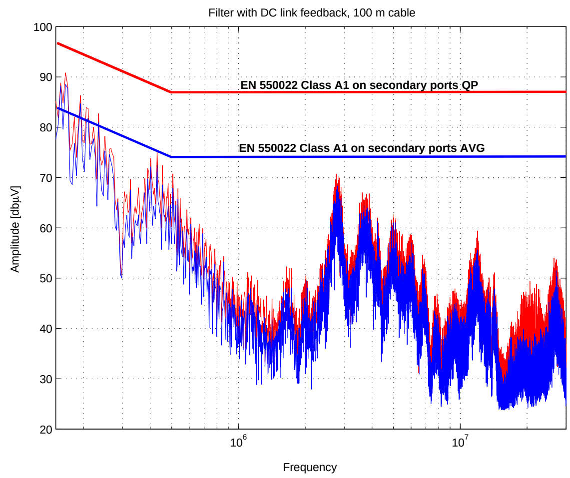



(c) Filter with DC link connection

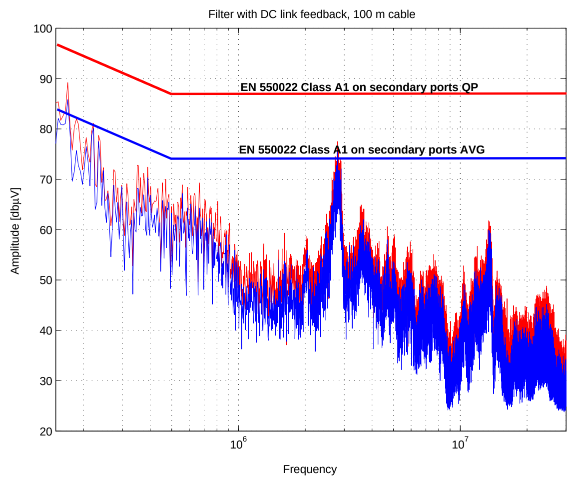
Fig. 8. CM conducted voltage noise in the 1 MHz – 30 MHz range.




(a) Motor and cable on GP




(b) Motor insulated, cable on GP

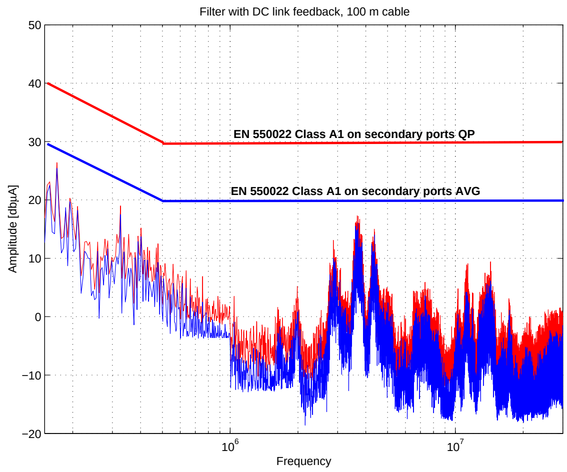



(c) Motor and cable insulated

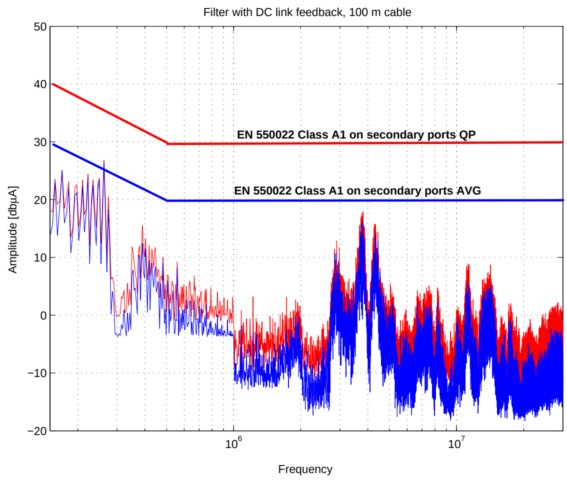
Fig. 9. CM conducted voltage noise in the 150 kHz – 30 MHz range, 100 m cable.

measured with the capacitive clamp, as shown in Fig. 6(c). The FFT of this voltage waveform also shows a major reduction in the noise, as seen in Fig. 7(c). The level of the noise in the 1 MHz - 30 MHz range shown in Fig. 8(c) is reduced very much. Just for the sake of comparison, if the CM voltage noise level in the 1 MHz - 30 MHz range is compared with the voltage limits from CISPR 22 (which is a standard for telecommunication ports of IT equipments) it would comply with the class A limit (for industrial environments, 87 dbV QP in the 0.5 - 30 MHz range).

The current measurements show relatively low noise levels therefore they are not shown for the tests with the 5 m cable. As in the case of CM voltage measurements, there is only little difference between the situation without filter and the situation with LC filter, especially in the lower frequency range (under




(a) Motor and cable on GP




(b) Motor insulated, cable on GP

Fig. 10. CM conducted current noise in the 150 kHz – 30 MHz range, 100 m cable.

150 kHz). There is a major improvement when using the filter with DC link connection. Again, just for comparison with the limits from CISPR 22, the current measurements would match class B (for home and office environment).

### *B. Experimental results with a long motor cable and output filter*

A second set of experiments was made with a 100 m cable. Because of this length the cable had to be coiled. Tests were performed in different situations varying the coupling between the cable and the ground plane and observing the behavior of the noise. The cable coil was placed at a 20 cm distance over the ground plane, after that it was directly placed on the ground plane. We also tried to wrap the cable coil in aluminium foil and ground it. These experiments were necessary because in reality the arrangement of the cable can vary from one installation to another. If the cable is placed in a metallic conduit or in a cable tray there is a higher capacity to ground while a cable feeding a trolley on a gantry crane has a bigger distance from the metallic structure and consequently there is a lower capacity to ground. The experiments were made with the motor both connected to the ground plane and insulated from it. Several measurements were made and the results were compared against the limits specified in CISPR 22, only as a reference. The CM voltage measurements were made with the commercial capacitive voltage probe that was calibrated for the cable type used in the experiments. The choice of this voltage probe has two main reasons: a more accurate measurement compared to the set-up using aluminium foil and a better shielding from external electric fields, especially cross-coupling from the big cable coil situated in the proximity of the voltage measurement point.

Fig. 9 shows the measured CM voltage in three situations: both motor and cable on ground plane in Fig. 9(a), cable on ground plane and motor insulated in Fig. 9(b) and both motor and cable insulated from ground plane in Fig. 9(c). It can be observed that when the cable is placed on the ground plane the noise level closely complies with CISPR 22 class A limits (industrial environment). Only in the 150 – 200 kHz region the average limit is slightly trespassed. The situation changes when both the motor and the cable are insulated from the ground plane. A resonance occurs at approximately 2.8 MHz, slightly trespassing the limit. Experiments show a dependance of this peak on the layout of the set-up. Therefore it is preferable to place unshielded cables in grounded cable trays and conducts.

The CM current measurements show relatively low levels, similar to the experiments with the short cable. Fig. 10 shows current measurements with the motor situated on the ground plane (Fig. 10(a)) and insulated (10(b)). It can be observed that the CM current meets the more strict class B limits (home and office environment).

## IV. Conclusion

In an ASD application using a PWM VSI, without any filtering at the output of the inverter, the CM conducted EMI levels in an unshielded motor cable are quite high, therefore in some applications the unshielded cable can not be used, due to EMC concerns. A classical LC filter does not improve significantly this situation. The tested output filter topology with connection to the DC link which works both in CM and DM, reduces the conducted EMI to acceptable levels even when long motor cables are used. When such a filter is used, at least in class A (industrial) environment, unshielded cables can be used in most situations without fearing EMC problems.

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