USING TRANSFER RATIO TO EVALUATE EMC DESIGN OF ADJUSTABLE SPEED DRIVE SYSTEMS

D. Zhao(1), J.A. Ferreira(1), H. Polinder(1), A. Roc’h(2), and F.B.J. Leferink(2)(3)
(1) Faculty of EWI, Technical University of Delft, Mekelweg 4, 2628CD, Delft, the Netherlands
E-mail: d.zhao@ewi.tudelft.nl
(2) University of Twente, Enschede, POBox 217, 7500 AE, The Netherlands
(3) Thales Netherlands, Henglo, The Netherlands

Abstract: This paper proposes a way to evaluate the conducted electromagnetic compatibility performance of variable speed drive systems. It is considered that the measured noise level is determined by two factors, the level of the noise source and the conversion efficiency of the propagation path from the source to the measurement equipments. They are corresponding to the two roles played by the converter. On the one hand, a converter provides the noise source and generates the noise current and voltage on the motor side with the cable and the motor. On the other hand, it acts as the propagation path with the DC bus and the rectifier to spread the noise generated on the motor side to the line side. The transfer ratio is defined as the ratio between the CM current on the motor side and the CM current on the line side. It can be used to evaluate the EMC design of a converter because it is independent of the cable and the motor. A simplified model is used to explain this characteristic. It can be measured when the converter is powered off. Verification is carried out by experimental results obtained from a 12-kVA laboratory system.

I. INTRODUCTION

Developments in power semiconductor components make it possible to increase the carrier frequency of voltage source PWM (pulse width modulated) VSD (variable speed drive) systems. The benefits that accompany this transition are enormous, for instance, improved control flexibility, energy saving, and less acoustic noise. Concurrently, the EMI (electromagnetic interference) related issues are aggravated for variable speed drive systems.

Besides the regulations from the manufactures, there are also compulsory standards from governmental agencies. The purpose of these regulations is to confine the EMI level after constructing complicated models with all parasitic coupling and components involved in noise propagation. These models can be established by measurements [5]-[7] or by analytic ways, for instance, the Partial Element Equivalent Circuit (PEEC) method [8]. Known from the constructed model, all components have impacts on the finally predicted noise level. An experimental example is given in [9], by extending the motor cable from 2m to 5m, the conducted emissions level changes up to 37dB. Therefore, the whole drive system is predicted or tested to find out if it is in compliance with standards. It is impossible to find an optimized EMC solution of a converter without taking the motor and the cable into account. It is also impossible to compare the EMC performance of two converters if different cables or motors are connected.

While the evaluation of a converter is very useful, as we know, components and installation inside the converter can produce significant impact to the final EMC performance of the complete drive system. Even converters based on exact the same schematic diagram can be built from different components and wired with different wires and routes. For instance, in some designs, wires are used to connect the heatsink or the PCB board ground to the inverter frame. In some other designs, the wire connections may be replaced with fastening screws. We need an evaluation method for the EMC design of the converter.

In this paper, by decoupling the measured noise level into two phases, namely noise source and transfer path, the two roles played by the converter from the EMC point of view can be decoupled as well. On the one hand, a converter provides the noise source and generates the noise current and voltage on the motor side with the cable and the motor. On the other hand, it acts as the propagation path with the DC bus and the rectifier to spread the noise generated on the motor side to the line side. The CM (Common Mode) current at the line side can be considered as the results which are converted from the CM currents at the motor side. This conversion efficiency is defined as the transfer ratio and can be used as a criterion for EMC evaluation.

Models are built to explain how the transfer ratio is determined. Looking into the models, we see that the transfer ratio is independent of the motor and the cable and is only related to the converter itself if measurement equipment is defined. It is verified by experiment subsequently. Therefore, it is meaningful to compare EMC performance of different converters by transfer ratio even if they have different loads.

The transfer ratio can be measured by the method called signal injecting [10]. It is compared to measurement result measured with the converter powered up. An obvious advantage of this method is preventing system damage or personnel injuries.
II. INVESTIGATIONS

In Fig. 1, the complete configuration of a typical PWM VSD system with the LISN (Line Impedance Stabilization Networks) is depicted. Two capacitors marked by star indicate the uncertain grounding method of the converter frame and the motor frame. One possibility is leaving them floating, then the connections can be presented by parasitic capacitors. If they are connected to ground, the connections can be modeled as small inductor.

II.1 Noise source

It is well known that the root of EMI of VSD is the switching event brought by PWM technology. The voltages between each pair of inverter output terminals change abruptly. This DM (Differential Mode) high dv/dt voltage is imposed between the motor terminals via the motor cable. Because parasitic capacitors exist in motor and motor cable, DM voltage generates high di/dt current as well.

Another source of high di/dt current is caused by the current commutations occurring in the PWM switching events. It is shown in Fig. 2. Contrary to DM noise, CM noise is induced with respect to the reference ground. If the DC-link midpoint is set as reference, the voltage in the output terminals of the converter change between $+V_{dc}/2$ and $-V_{dc}/2$. The CM voltage of the output terminals of the converter to the ground jumps among discrete voltage levels, and never goes back to zero. The change frequency is three times the switching frequency of the inverter. This stepwise signal produces CM noise current with the parasitic capacitors existing between the motor winding and the motor frame. A measurement result presented at Fig. 3 clearly shows this causality chain.

Fig. 2. Diagram to illustrate DM fast transient current

Fig. 3. Measured CM voltage and CM current

II.2 Measurement equipment

The non-symmetric voltage measured by the LISN is actually the voltage drop of the symmetric (DM) current and asymmetric (CM) current that flowing through the 50Ω impedance. Instead of using LISN, we prefer to use the current measurement method proposed in [11] because it avoids extra electrical connections and modifications to LISN compared to the separator proposed in [12]. Another advantage is that this method can also be applied at the motor side and the DC bus of the converter. By enclosing the three phase wires with a current probe, the CM current is measured. The DM current can be determined via the wiring configuration depicted in Fig. 4(b).

(a) $I_{L1} + I_{L2} + I_{L3} = 3I_{CM}$

(b) $2I_{L1} - I_{L2} - I_{L3} = 3I_{DM}$

Fig. 4. Using current probe to separate CM and DM
The superposition principle holds. If the cross transferring is ignored between CM and DM, the following equation exists.

\[ V_{\text{LISN-L1}}(f) = 50 \times I_{L1}(f) \]
\[ = 50 \times (I_{\text{CM1}}(f) + I_{\text{DM1}}(f)) \]
\[ = 50 \times (T_{\text{CM}}(f)I_{\text{CM1}}(f) + T_{\text{DM}}(f)I_{\text{DM1}}(f)) \]

(1)

Here,
- \( I_{L1} \): Noise current in the line side of phase L1
- \( I_{\text{CM1}} \): CM current in the line side of phase L1
- \( I_{\text{DM1}} \): DM current in the line side of phase L1
- \( I_{\text{CM2}} \): CM Noise current in the motor side
- \( I_{\text{DM2}} \): DM Noise current in the motor side
- \( V_{\text{LISN-L1}} \): Noise level measured by LISN of phase L1
- \( T_{\text{CM}} \): Transfer ratio of CM current
- \( T_{\text{DM}} \): Transfer ratio of DM current

In Fig. 5, CM and DM current are compared at the line side of the converter after separation, which can mean that the dominant noise mode is CM beyond 700 kHz. The CM noise source in motor side and the CM transfer ratio determine the final noise level measured in LISN above 700kHz. In the rest sections, the facts determining the CM transfer ratio are analyzed.

### III. MODELS

The first equivalent CM circuit is given in Fig. 6. The DC-link, the output terminals of the converter and the heatsink are represented by three nodes in the circuit diagram which is applicable in high frequency [13]. The common mode voltage is represented by the voltage source between terminals and DC bus. Stray capacitors from the cathode of the rectifier and the collectors of the switches to the heatsink are included as capacitors. The grounding connections are represented by small inductors. The high frequency behavior of motor is approximated by series connected inductance and resistance circuit. The motor cable is represented by a lumped-T model since the cable is electrically short. Dielectric losses are not included here. The rectifier is treated as propagation path only due to its relatively slow switching behavior [13].

The CM equivalent circuit model is further simplified to the model given in Fig. 7. It can be used to calculate the transfer ratio between CM current at the motor side and CM current at the line side.

![Fig. 6. CM Equivalent circuit of VSD](image)

Here,
- \( C_{\text{cab}} \): Capacitor from motor cable conductor to ground
- \( L_{\text{cab}} \): Motor cable conductor inductance
- \( C_{\text{wf}} \): Capacitance between motor winding and frame
- \( R_{\text{wf}} \): Resistance between motor winding and frame
- \( C_{\text{stray1}} \): Parasitic capacitor from collectors of upper switches to heatsink
- \( C_{\text{stray2}} \): Parasitic capacitor from collector of lower switch to heatsink
- \( C_{\text{stray3}} \): Stray capacitor from cathode of rectifier to heatsink
- \( Y_{\text{cap}} \): Possible existing Y capacitors
- \( L_{\text{g1}} \): Stray inductance of grounding cable of motor
- \( L_{\text{g2}} \): Stray inductance of grounding cable of converter

![Fig. 7. Simplified CM Equivalent circuit of VSD](image)

Here,
- \( Z_{1} \): Impedance of paralleled \( C_{\text{stray1}}, C_{\text{stray3}} \) and possible existing Y capacitor
- \( Z_{2} \): Impedance of \( C_{\text{stray2}} \)
- \( Z_{4} \): Impedance of the grounding wire of converter
- \( Z_{5} \): CM impedance of motor cable and motor
- \( Z_{6} \): Impedance of mains cable, possible existing CM choke and power supply. Mostly, it is stabilized by LISN.

Therefore, the transfer ratio can be expressed as,

\[ T_{\text{CM}}(f) = \frac{I_{\text{CM1}}(f)}{I_{\text{CM2}}(f)} = \frac{Z_{1}Z_{2} + Z_{2}Z_{3} + Z_{3}Z_{4} + Z_{4}Z_{5}}{Z_{1}Z_{2} + Z_{2}Z_{3} + Z_{3}Z_{4} + Z_{4}Z_{5}} \]

(2)
Under the condition that $Z_2 >> Z_1, Z_3, Z_4, Z_5$, which is satisfied in most situations, the transfer ratio can be simplified as,

$$ T_{CM}(f) = 1 - \frac{Z_5}{Z_1 + Z_3 + Z_5} \quad (3) $$

Obviously, it is independent of the motor and cable.

**IV. EXPERIMENTS**

A VSD rated at 400V, 50Hz and 12 kW was used. The 380-V, 7.5-kW, 4-pole induction motor ran with no load. The only EMC suppression components inside the converter are three Y capacitors of 0.1µF connected to the enclosure.

A three-phase LISN (50 Ω/50 µH) is fixed at the line side in order to decouple and standardize the inverter input from the grid. The adopted measuring system was a Fischer F-75 current probe (bandwidth from 10 kHz to 500 MHz). Comparing the noise current level measured at the line side and that at the motor side, the transfer ratio can be calculated.

**IV.1. CM transfer ratio and DM transfer ratio**

The first experiment is done to verify how the transfer ratio is influenced by the grounding configuration. The converter is tested leaving it floating firstly, and then the experiment is repeated with the converter grounded.

As shown in Fig. 9(a), DM transfer ratio is independent of the grounding configuration. It is mostly related to the DM suppression components inside the converter. The DC bus capacitor has the largest impact. Contrary to DM transfer ratio, CM transfer ratio seems influenced by the grounding configuration significantly. The result is shown in Fig. 9(b). It is notable that the grounding configuration is an important factor in EMC design.

**IV.2. CM transfer ratio is independent to load**

This experiment is introduced to verify the conclusion that the CM transfer ratio is independent of the load and cable.

The comparison is done by changing motor cable from 2m to 5m. Fig. 10 (a) illustrates the measured CM noise current at the motor side. The transfer ratio is calculated afterward and drawn at Fig. 10 (b). Obviously, the peaks in the spectrum of noise current are shifted, but the transfer ratio keeps the same. This measurement proves the hypothesis that transfer ratio is fixed even the noise source is changed.

**IV.3. CM transfer ratio is dependent to EMC design**

In this experiment, the CM transfer ratios with and without Y capacitor are compared.
In the design without any EMC suppression components, the noise current flows along the motor cable, the motor winding, the ground, the LISN, the line cable and the DC bus. A transfer ratio close to unity is expected.

Mostly, Y capacitors are used in the converter to suppress EMI. They are connected to the enclosure of VSD. The modification to the equivalent CM circuit is adding the Y capacitor besides $C_{stray3}$. It is given in Fig. 11.

![CM Equivalent circuit of VSD with Y capacitor](image1)

Now, the noise current is formed along the motor cable, the motor winding, the ground, the grounding cable of the converter, the Y capacitors, and the DC bus, due to the low impedance of the Y capacitor. This loop is depicted by solid line in Fig. 11. Much lower transfer ratio is expected according to the current division between Y capacitor and power supply / LISN.

![Transfer ratio comparison between with and without Y capacitor](image2)

The transfer ratio comparison is shown in Fig. 12. After adding the Y capacitor, the transfer ratio is reduced drastically up to 12MHz, which proves that this EMC design is better than the design without the Y capacitor.

**IV.4. Measure the CM transfer ratio by signal inject**

The benefit of using external pulse source is to avoid turning on the drive and the motor. Therefore, it is more safety. The noise source is a 100KHz pulse generator. It is injected in the motor side of the converter as Fig.13 depicted. Current probes are placed on the line side and motor side of the converter to measure the CM current. The transfer ratio is calculated afterwards and shown in Fig. 14. The result got via voltage injection is marked with stars. Compared to the result measured when drive and motor are powered up, the shape is similar up to 4MHz.

![Measure CM transfer ratio by signal inject](image3)

![Measure CM transfer ratio with drive powered up and powered off](image4)

**IV. CONCLUSION**

This paper aims at presenting the analysis of the noise source and transfer path inside a VSD system. It is believed the CM noise current at the motor side is predominant noise source of the VSD system. The transfer ratio between CM noise current at the motor side and CM noise at the line side decides how good an EMC design of VSD system is. It provides a quantity method to rate the noise conversion efficiency which is the key of an EMC design of VSD. Another merit of this method is that it is independent of the load and cable.

By decoupling the determination of the noise level at the line side into source and conversion efficiency, methods can be classified into two groups to decline the emission propagating into the grid. One possibility is suppressing the noise in the source. Adding output CM choke is such kind of solution. Another possibility is reducing the transfer ratio. One corresponding method is adding Y capacitor inside the converter. Through the defined transfer ratio, the impact to the EMC design of a converter brought by changing components placement inside the converter can also be quantitatively evaluated. The
measurement can be done by voltage injecting when the converter is powered off. 
Our research task is now oriented towards decreasing the transfer ratio by optimization of relevant components.

V. ACKNOWLEDGEMENT
This work is an IOP (Innovative Research Project) project and financed by the Dutch Ministry of Economic Affairs.

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