Analysis of Common Mode Currents and Harmonic Pollution at Supplying Induction Motors from Static Converters with Variable Modulation Frequency

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***Abstract*— The problems of Electromagnetic Compatibility (EMC) in three-phase systems are less studied than single-phase or direct current, due to the smaller ratio of emissions relative to the rated power of such systems. This paper is focused on the problem of emissions in three-phase variable frequency drive systems in the low-frequency EMC range, specifically on the common mode current through the connected ground wire between the static converter and power grid. The common mode current is determined to be variable depending on switching frequency. For a deeper understanding Fast Fourier Transform was used to decompose the signal. Main parameter to understand the magnitude of common mode current was the RMS of the current. The decomposition showed a significant DC component which cannot be picked up by the used RF probe, thus presenting a noise offset necessary to be considered when calculating the total effective value of common mode current. The analysis was made on the time-domain representation and the frequency behavior of the converter. The paper suggests that the standard measurement in the low-frequency range and the picked-up signal are investigated enough, as there is a disparity in the impact of emissions in the low-frequency range compared to what off-the-shelf devices have to offer, which are standard compliant, but still present considerable emissions.**

Keywords—variable frequency drive, modulation frequency, three phase system, common mode current.

I. Introduction

Industrial applications, power distribution and high-power electric transportation all use three-phase current topology. In this system defining EMC, and signal and power integrity (SIPI) standards and definitions requires additional criteria, different from the direct current (DC) topology or alternative current (AC) single phase topology. Contrary to this fact, three-phase EMC and power quality (PQ) is the least studied field of EMC and SIPI due to power distribution and susceptibility of equipment in three-phase systems. Single phase AC or DC systems are better suited to low power applications, which are more susceptible to electromagnetic interferences, while three-phase AC systems are better suited for medium- and high-power electric conversion of energy, such as lighting and electromechanical conversion, where EMC issues are less obvious [1, 2].

Variable frequency drives (VFD) are the most used power converters in industry. Current development trends for VFD systems are directed at determining optimal efficiency in control and converter topology. Another criterion of considerable importance in the development of power electronics is considering the power quality and EMC issues of power converters. Methodologies presented in [3-5] show improvement in harmonic production for IEEE standard compliance, such as the IEEE 1459-2010, by adopting a multilevel inverter. Other improvement techniques rely on improving the modulation techniques, such as space vector modulation [6], random PWM [7] and selective harmonic elimination [8, 9], last one being more common for power conditioners. Other studies suggest implementation of filtering techniques in the network of the VFD, for harmonic compensation [10, 11], or common mode current elimination [12]. Common mode (CM) current is an especially important issue, which was found to affect the ball bearings and other parts of the induction motor (IM) [13]. The producers of VFD equipment thus must comply with EMC standards, which revolve around older semiconductor technologies, siliconbased transistors, and diodes. New semiconductors, like those based on silicon carbide or gallium-natrium metal-oxidesemiconductor field-effect transistors (MOSFET), broaden the field of efficient usage and used frequencies in electric drives but set new problems for EMC analysis.

To determine the limitations of EMC test standards and subsequent off-the-shelf (OTS) equipment for measuring EMC, an analysis of conducted EMC was done in two ways. Firstly, a three-phase linear impedance stabilization network (LISN) compliant with CISPR-16 or EN 61000 standards was used to measure the EMC of the VFD with a spectral analyzer. Secondly, an oscilloscope was used to measure the data and a post-processing with Fast Fourier Transform (FFT) was applied to determine the spectral components of the interference. The time-domain data were denoised using wavelet denoising, explained in [13]. The two methods were applied to identical varying conditions of modulation frequency and output frequency of the VFD to an IM with no mechanical load.

II. Experiment Setup

To measure the EMC effects of OTS VFD, the set-up (Fig. 1) begins from the three-phase power supply of 400

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VAC, which supplies the VFD, through a three-phase four-wire CISPR-16 compliant LISN (Fig. 2). The VFD supplies a 0.75 kW IM, which has no mechanical load connected. The measurement devices used were a spectrum analyzer and a digital oscilloscope (Fig. 2), for which we used a RF current probe with frequency measurement range 20 Hz to 8 MHz and a 600VAC voltage probe.

Signal processing was done using Wavelet (WT) and FFT. A five-level Daubechies-mother WT was used to denoise the signals, and FFT was used to decompose the signals into harmonic components.

To understand better the impact of conducted emissions in three-phase applications, the data was harvested for varying output frequency by the VFD to supply the IM, and varying modulation frequency. The experimental settings are presented in TABLE I

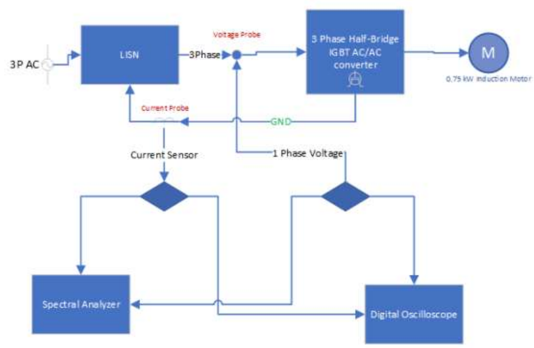

Fig. 1 Experimental set-up

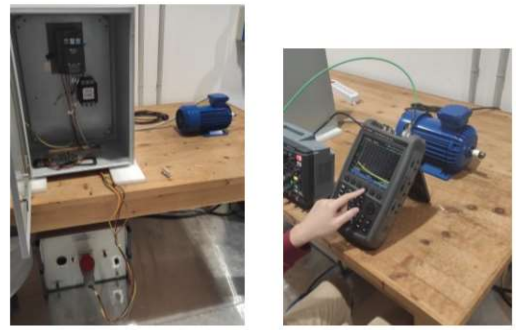

Fig. 2. Experimental set-up: left – LISN, VFD, IM; right – digital oscilloscope, spectral analyzer and IM

TABLE I. TESTING SETTINGS OF FREQUENCY

Modulation Frequency, kHz	VFD output frequency, Hz
2	2
	50
	100
7	2
	50
	100
15	2
	50
	100

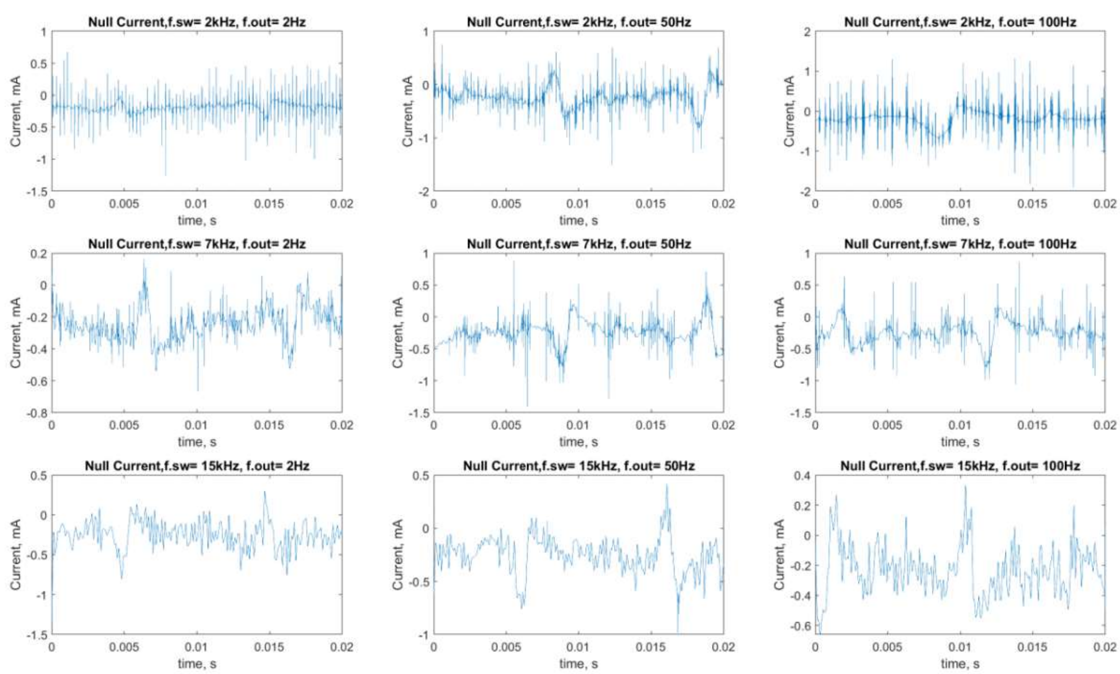

Fig. 3 Denoised waveforms of one period of CM current for varying output (f.out) and switching frequency (f.sw)

III. Common Mode Current Analysis

A. Time-domain measurements

The full range of measured data is presented in fig. 3. The presented data is already denoised with a high level denoise using the wavelet transform. It can be observed that it was not enough still to eliminate all the noise. Considering that the experimental set-up included a three-phase LISN, this impulse noise is generated by the VFD.

As can be seen in fig. 4, the data were heavily polluted by environmental noise, since the tests were not done in anechoic chambers, thus simulating real test environment. The first step taken was the denoising of current and voltage signals. The signals before and after denoise are presented in Figs. 4,5. The denoise method was suggested in [14], as using a small signal with variable level of noise.

Visual analysis of null current (Fig. 3) shows a growing level of distortion in amplitude with output frequency. Suggesting that the higher frequency is more energy consuming on the motor part. The switching frequency, on the other hand, imposes a lower absolute level of CM current on the system, as amplitude levels in graphs drop inversely proportional to the switching frequency.

B. Frequency-domain data analysis

The frequency-domain analysis of the CM current was done in two ways. Firstly, the spectrum analyzer gathered spectral measurements (Fig. 5). These data present the logarithmic values of the measurement value, which can be compared to the limits imposed by EMC standards. Secondly, the time-domain measurements were processed by Fast Fourier Transform (FFT), to determine harmonic composition of current, and identify the predominant spectral components.

The output of data from the spectral analyzer (Fig.5) is presented in dBμV, while the current sensor provides the

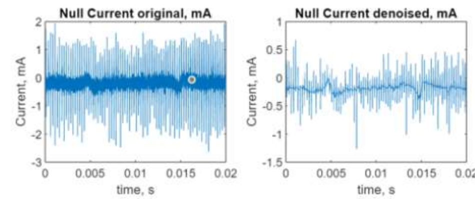

Fig. 3. Denoising of CM current via wavelet transform. Left – original, right – denoised.

current value in the ground wire, which is the flow path for the common mode current. Fig. 5 presents the CM voltage transferred by the spectral analyzer. The CISPR-11 standard imposes limits on the frequency composition of voltage for industrial, scientific, and medical equipment - radio-frequency disturbance characteristics. The lowest frequency range of conducted emissions is from 150 kHz, with imposed limit of 66 dBμV for average value. Fig. 5 shows compliance to these limitations. So, the CM current does not interfere with the EMC standard.

To have an overview of energy impacting the CM circuit, the RMS of the current was chosen, and determined for each testing case and presented in a by-variable condition in Fig. 6. The surface plot shows that the highest RMS value is for 2 Hz output frequency and 15 kHz switching frequency. In Fig. 6 it can also be noticed that lower switching frequency generally leads to lower energy flowing from the VFD into the ground wire while no load is present. That is a determining factor of the switching losses in the semiconductor elements, which grow with the modulation frequency.

On the other hand, FFT decomposition showed that the highest weight component of the CM current is the DC component. The CM current has a significant DC component,

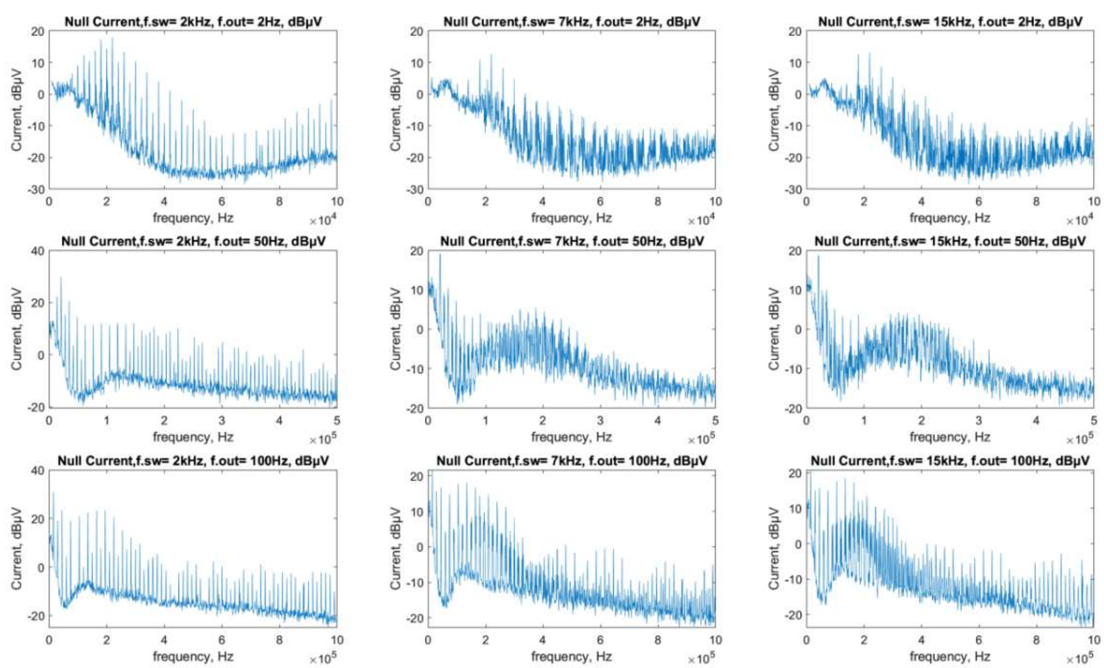

Fig. 5. Spectral measurements of the CM current of the VFD

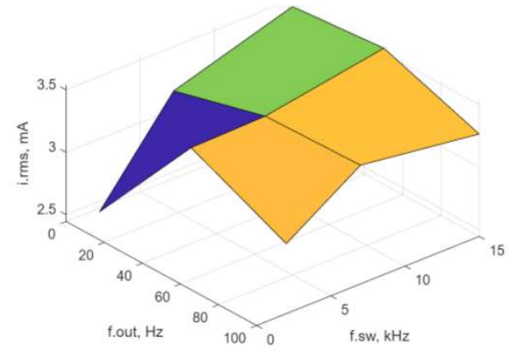

Fig. 6. RMS of the CM current.

also observed in Fig. 3. DC current can be an important factor in EMC compliance testing, with appropriate equipment according to EMI measurement standards. In our case, the RF probe measures components with frequency starting from 20 Hz, thus excluding the DC component. This seems to be constant EMC noise picked up by the oscilloscope and/or the measuring probes. Thus, it must be eliminated from calculating the RMS of the current.

A general observation from Fig. 6 is that the RMS component grows alongside the switching frequency, while output frequency presents some variability.

IV. Conclusions

Inclusion of VFD in the power network comes with EMC risks that are being under-represented in current standards for the low frequency EMC range, 2 to 150 kHz.

This research suggests that VFD will include a variable level of CM current into the power grid, depending on both the switching frequency of the semiconductor devices and the output frequency of the VFD. In the presented case, the raise of switching frequency will conduct to a raise in RMS and spectral composition of the CM current, concluding with the necessity of CM filters for applications that use such frequency. On the other hand, the lower the output frequency, the higher the RMS of the CM current.

If there is a ground wire present in VFD connected loads, the CM can be filtered according to the output frequency and the power levels of the leakage. The same CM current should be filtered on the output side of the VFD, since the leakage current can cause extra damage to the motor drive.

This research is valid for all motor drives, including power trains of electric vehicles and railway locomotives. In the case of vehicles, the CM current will leak through the mechanical moving parts, causing them to deteriorate faster. Industrial producers of VFD equipment should test the systems with such conditions, adding an application specific load profile to the motor, to ensure that the electric drive serves reliably and does not distort the power quality and EMC in the grid.

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