HARMONICS OF INDUSTRIAL POWER ELECTRONIC CONVERTERS IN THE FREQUENCY RANGE UP TO 10 KHZ

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ABSTRACT - This paper refers to fundamental investigations and simulations of conducted electromagnetic interference emissions produced by power electronic devices in a frequency range from 2 to 10 kHz. The emissions of different industrial power converters were measured and compared. The influence of different working conditions over the altitude of the EMI are represented. Simulations of the power converter system including the line impedance stabilisation network certify the measurements.

1. INTRODUCTION

In order to understand the principles of origin and expansion of the disturbances, it is necessary to analyse them by using simple models. The high-frequency currents of high power electronic converters cause a voltage drop at the impedance of the mains supply (low-voltage network, communication network etc.). This voltage drop is called the interference voltage.

The impedance depends on the specific environments e.g. industrial or residential areas. So it can be that the same instrument produce varying interference voltages at different mains connection points. There are two possibilities to measure the interference:

a) measuring of the current
b) measuring of the voltage drop over a known impedance

The measuring of conducted electromagnetic interference emissions produced by power electronic devices is divided into two frequency ranges as shown in Fig.1. Both frequency ranges are set by standards.

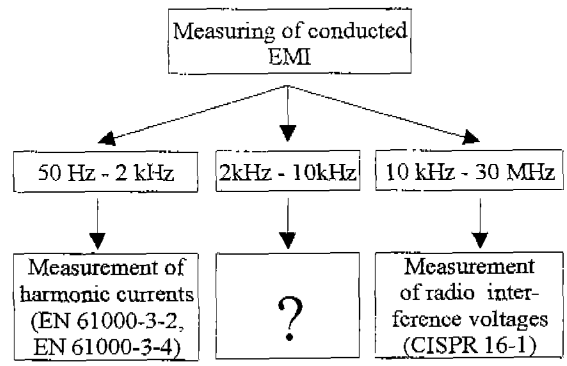

Fig. 1: Division of the frequency range from 50 Hz to 30 MHz

Measurement of current harmonics

The measurement of current harmonics in the frequency range from 50 Hz to 2 kHz is governed by European Standard 61000-3-2 and 61000-3-4 (for currents > 16A per phase). The currents are measured across a current sensing part. The resulting voltage is presented in the frequency range with the help of different processes like frequency domain measurements or time domain measurements [5], [6]. This standard approves both time domain measuring systems and frequency domain measuring systems.

Measurement of interference voltages

The measurement of low-frequency disturbances of power electronic devices within the frequency range from 10 kHz to 30 MHz is specified in the standard CISPR 16-1. It is based on the determination of the voltage drop across a LISN (LISN - Line Impedance Stabilisation Network) [3], [4]. The LISN allows reproducible measuring results independent on the real supply network impedance. It also prevents the distortion of the measurements due to disturbances already present in the supply network. There are three essential tasks of the LISN:

a) to decouple the measuring system from the network
b) to realize a defined impedance of the mains supply
c) to make a strong damping of the 50 Hz mains voltage

2. MEASURING SYSTEM

The existing LISNs for the measurement of interference voltages greatly differ in construction. Functionally however they are all equivalent. From this point of view it makes sense to modify the LISN specified in CISPR16-1 for the function it should accomplish.

Modification of the LISN

a) high-frequency decoupling from the mains

The decoupling from the power supply is usually done by a low-pass filter. Each power lead including the neutral lead has its own decoupling network which isolates the equipment from high-frequency currents in the mains. In order to guarantee a decoupling for the frequency range to be examined, the cut off frequency of the low-pass filter has to be shifted into the range below 2 kHz. This can be accomplished by adding a further CR-combination at the mains port of the LISN. An exact design of the low-pass filter can be seen in Fig.2.

b) definition of the mains impedance

The European Standard CISPR16-1 specifies an impedance of the LISN of (50 µH + 5 Ω) parallel to a 50 Ω measurement resistance for the frequency range between 10 kHz and 30 MHz. In the frequency range to be examined however the actual impedance |Z| is below 5 Ω [2]. In order to determine the impedance more accurately, a further impedance (540 µH + 40µF + 2,3 Ω) was added to the LISN.

c) decoupling and/or damping of the mains voltage

All the LISNs which are commonly used determine the same mains impedance. Since the full power of the 50 Hz fundamental would destroy the measuring equipment it has to be attenuated by using a high-pass filter. In the frequency range from 10 kHz to 30 MHz the output attenuation is either zero or has a set value. According to CISPR 16-1, a CR-high-pass filter is used for decoupling the low-frequency signals (R=50 Ω, C=0,25 µF). The damping of the filter is non-negligible in the frequency range from 2 to 10 kHz and can be calculate with equation 1.

$$|G(j\omega)| = 20 \cdot \log\left(\frac{1}{\sqrt{1+\left(\frac{1}{\omega C \cdot R}\right)^2}}\right) \qquad (1)$$

The result of this three modifications can bee seen in Fig.2.

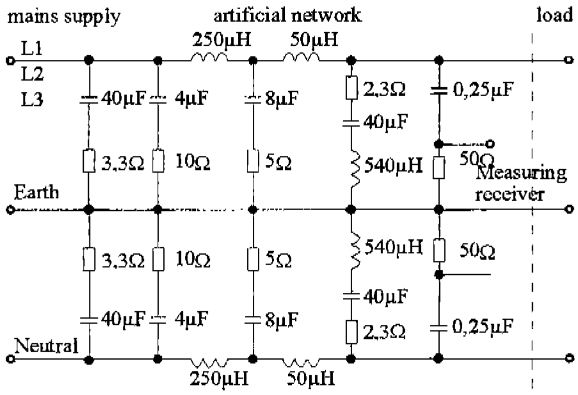

Fig. 2: Modification of CISPR16-1 network [1]

3. ERROR ANALYSIS

The impedance of the network increases with rising frequency. In the frequency range from 10 kHz to 30 MHz the impedance may be represented by a network of (50 µH + 5 Ω) parallel to 50 Ω. It can be seen, that with increasing frequency a constant current amplitude will induce a higher voltage drop. In other words, the same voltage drop will result from lower currents at higher frequency. Since the operating currents are included in the measurement they cannot be considered to be accurate for higher frequency ranges. This will be shown more clearly later on.

Measuring error of the current measurement

For measurement of current harmonics to concrete limits up to the 40^{th} harmonics of the fundamental frequency limits are specified in the European Standard 61000-3-2. These limits apply to instruments of the class A (for genuine three-phase equipment's). In this standard is fixed also a maximum measuring error of 5 % of the allowed limit or 0,2 % of the input current (which ever value is larger) [5].

That means, a set error limit is specified in European Standard 61000-3-2. This limit has a value of ± 32 mA for input current of 16 A. The limit for the 40^{th}

harmonic (EN61000-3-2) of the mains current $\geq 16A$ is given by 46 mA.

Assuming that the threshold values in the frequency range from 2 kHz to 10 kHz have to be below the limits of the European Standard 61000-3-2, a current measurement by this procedure does not appear to be accurate. The measuring error of the powermeter with integrated FFT used for this project was specified as follows:

$\Delta I = \pm (0.05\,\%$ of the measured value + 0.05% of the measurement range)

For a nominal current of 16 A and a measuring range of 30 A , there is a measuring accuracy of

$\Delta I = \pm (0.008\ A + 0.015\ A) = \pm 0.023\ A = \pm 23\ mA$

The resulting measuring error relative to the smallest threshold value of the harmonic current $I_{40} = 46$ mA is thus:

$$I\%_{meas} = \frac{\Delta I}{I_{40}} = \frac{0.023\,A}{0.046\,A} = 50\% \qquad (2)$$

The measuring accuracy of the powermeter is also relativ bad.

Measuring error of the voltage measurement

The error occuring in measurements of the interference voltage is determined by the measuring accuracy of the measuring receiver. This measuring accuracy is specified by the producer as $\Delta V = \pm 1$ dB maximum.

If a voltage is calculated from the threshold value of the 40^{th} harmonic (46 mA) and the mains impedance at 2 kHz (approximatly $|Z_{Mains}| = 2\ \Omega$), according to

$$\hat{V}_I = |Z_{Mains}| \cdot \hat{I}_{Harmonic} \qquad (3)$$

The amplitude of the interference voltage is 92 mV. This corresponds to a tension of $V_s = 99.3$ dB(μV). There is a relative measuring error in the measurement of the interference voltage of:

$$V\% = \frac{\Delta V_I}{V_I} = \frac{103{,}2\,mV - 92\,mV}{92\,mV} = 12.2\% \qquad (4)$$

This accuracy is a result of the strong damping of the 50 Hz component by the LISN. Therefore the measuring receiver can be very sensitively. The difference in the measuring accuracy between this two procedures is the main reason for measuring the interference voltage across a standard LISN.

4. MEASURING RESULTS

The conducted EMI caused by the switching frequency of different three-phase power converters were measured in the frequency range between 2 and 10 kHz. For that purpose the investigated converters were divided into the following basic types:

a) three phase pulsed rectifier with DC Voltage Link
b) three phase rectifier with capacitive load and following three phase pulsed converter

An example for both types show Fig. 3 and 4.

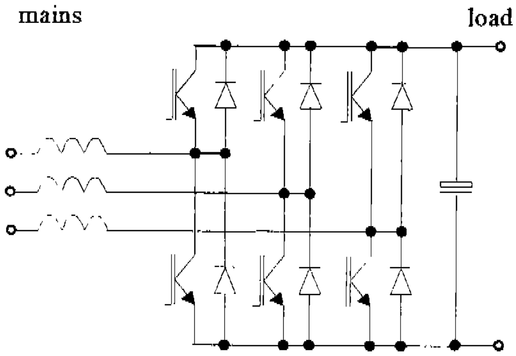

Fig. 3: Three phase pulsed rectifier with DC Voltage Link

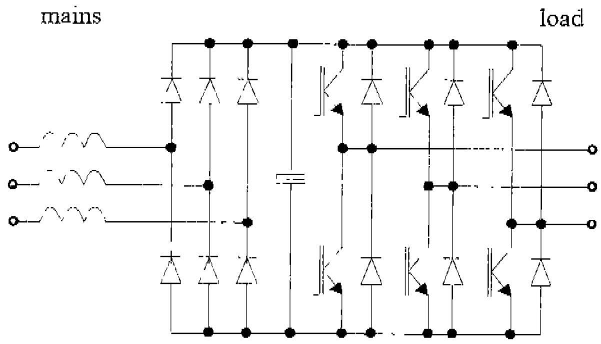

Fig. 4: Three phase rectifier with capacitive load and following three phase pulsed converter

The measurements were done under the following conditions:

a) variation of the load current value
b) variation of the kind of load

Influence of the load current

To see the influence of the load current, the emissions of all converters were measured with zero-load and full load (pure resistive load). The highest emissions are produced by three phase pulsed rectifiers with DC voltage link. The highest emissions (about 134 dB(μV)) of all three phase pulsed rectifiers with DC Voltage Link are independent on the load current. A typical measurement curve is shown in Fig.5. The upper curve is valid for full load current and the lower curve was done without load current.

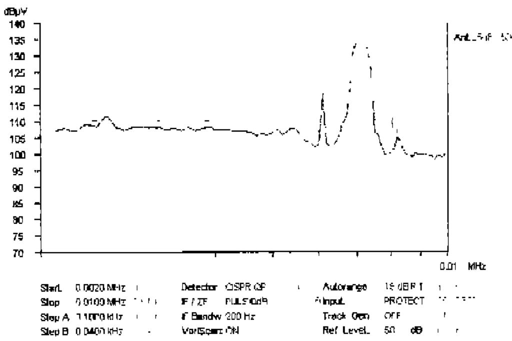

Fig. 5: Emissions of three phase pulsed rectifier with DC Voltage Link (influence of load current)

The emissions of three phase pulsed rectifiers with DC Voltage Link are depending on three important facts:

- the altitude of the DC-link voltage
- the impedance of the converter choke
- the impedance of the supplying mains

The emissions of the three phase rectifiers with capacitive load and following three phase pulsed rectifier are much lower and are depending on the load current (Fig. 6).

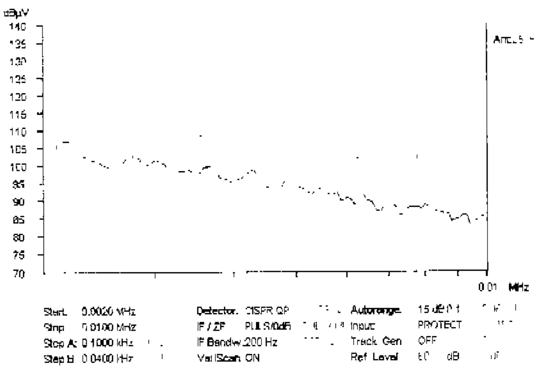

Fig. 6: Emissions of three phase rectifier with capacitive load and following three phase pulsed converter (influence of load current)

Influence of the kind of load

To see the influence of the load the emissions of the converter were measured with pure resistive load and with motor load. In Fig.7 it can be seen that the emissions of three phase pulsed rectifiers with DC Voltage Link are independent on the kind of load.

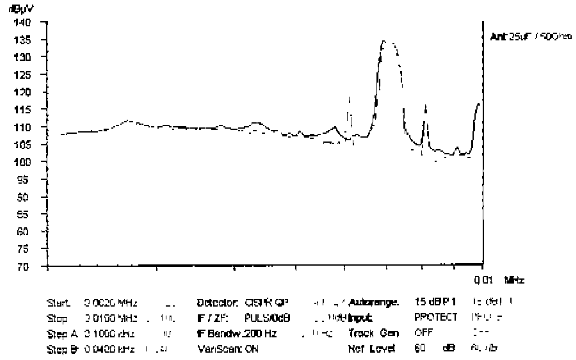

Fig. 7: : Emissions of three phase pulsed rectifier with DC Voltage Link (influence of kind of load)

In contrast to Fig.7 the emissions of the three phase rectifiers with capacitive load and following three phase pulsed converter depend on the kind of load. The emissions with connected motor load are higher than with resistive load (Fig 8). The upper curve is valid for motor load current and the lower curve was done with resistive load current.

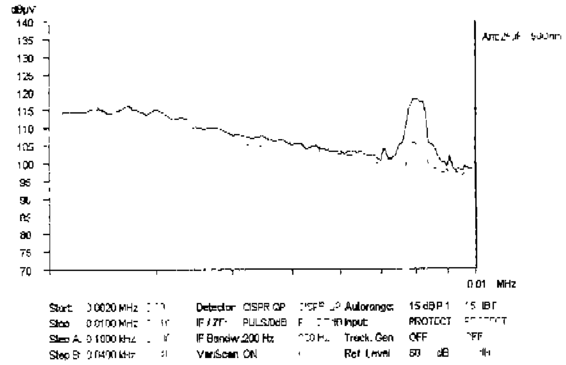

Fig. 8: Emissions of three phase rectifier with capacitive load and following three phase pulsed converter (influence of kind of load)

Highest emissions

For the measurement of the highest emissions the converters were subdivided in three groups:

Group a: three phase pulsed rectifiers with DC Voltage Link - I > 16A

Group b: three phase pulsed rectifiers with DC Voltage Link - I ≤ 16A

Group c: three phase diode rectifiers with capacitive load and following three phase pulsed converter - I > 16A

For all inspected devices with different switching frequencies and power ranges was done an emission measurement like shown in Fig.5 and the higest level was marked in Fig.9. By this way a significant curve was created for each group of converters.

As well, it was measured that the highest level of the emissions is not located at a switching frequency of the inverter but 50 Hz or 100 Hz beside this frequency. This is the result of the different modulation techniques of the converters.

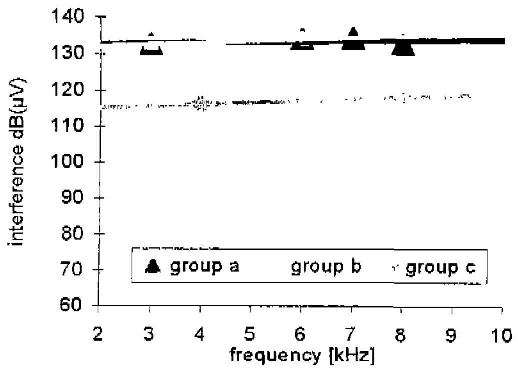

Fig. 9: Highest emissions of investigated converters

5. CONCLUSION

The paper deals with the selection of a suitable measuring procedures for the measurement of conducted EMI in a frequency range 2 to 10 kHz. Because of the higher accuracy of the voltage measurement using a LISN in opposition to current measurement this method was preferred for determining interferences. Since the required LISN is not standardized for the frequency range from 2 kHz to 10 kHz this paper suggests a modification to the existing and standardized LISN.

To evaluate the given converters regarding the emissions a variation of the load current and the kind of load was done. The highest level of interferences was produced by switched rectifiers independent on the load current and the kind of load.

The maximum of the emissions was found 50 or 100 Hz beside of the switching frequency of the converter. The emissions of three phase diode bridges with a capacitive load are significant lower but depend on the load current and the kind of load.

6. REFERENCES

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