

About Measurement Uncertainty of Conducted Emissions Generated by a Variable Speed Drive

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Abstract – An experimental study about uncertainty in measurements of conducted emissions generated by a variable speed drive in the frequency band 150 kHz to 30 MHz due to variations in the power voltage, driving conditions and amplitude of torque applied to an electrical load is presented. A global index based on the weighted distance between measurements and standard limits is introduced to help to single out which factors have the largest influence on emissions. Results show that frequency of motor and torque applied to it can in fact cause relevant changes. One interesting takeaway is that when testing power drive systems for compliance to conducted emission standards, more specifications should be given about operating conditions in order to keep uncertainty related to test conditions at acceptable levels.

I. Introduction

Power Drive Systems (PDS) pose interesting questions in terms of electromagnetic compatibility. Most modern motor drives use very high frequencies for currents and voltages, which make unintentional current paths. The electromagnetic interference signals can be transmitted from any source to a susceptible unit by means of conduction, radiation or common impedance coupling. These disturbances can modify the characteristic parameters of the electrical network with serious consequences on other users connected; in addition they can also affect the correct behaviour of the measurement and control system of the drive.

Studies by other authors have shown that the main cause of conducted emissions must be sought for in the high voltage gradients over time (dV/dt) that pertain power electronics [1], though only in the past decade has a detailed analysis of the high frequency behaviour of asynchronous motors been undertaken [2]. Furthermore, a thorough examination of electromagnetic compatibility standard for PDS [3] shows that the choice of most test conditions is left to the experimenter, thus introducing a number of degrees of freedom that affects the overall measurement uncertainty and therefore significance of measurement results. Other authors have already shown the impact of cable length, distance in between and inverter's PWM (pulse's width modulation) frequency and the PWM strategy [4], and behaviour under not-nominal conditions [5]-[8]. Continuing preceding works, the aim of the presented research is to evaluate possible additional causes of uncertainty in conducted emissions measurements to help determine the worst case for PDS compatibility tests and enhance reliability of standard tests in terms of correspondence with actual operation conditions.

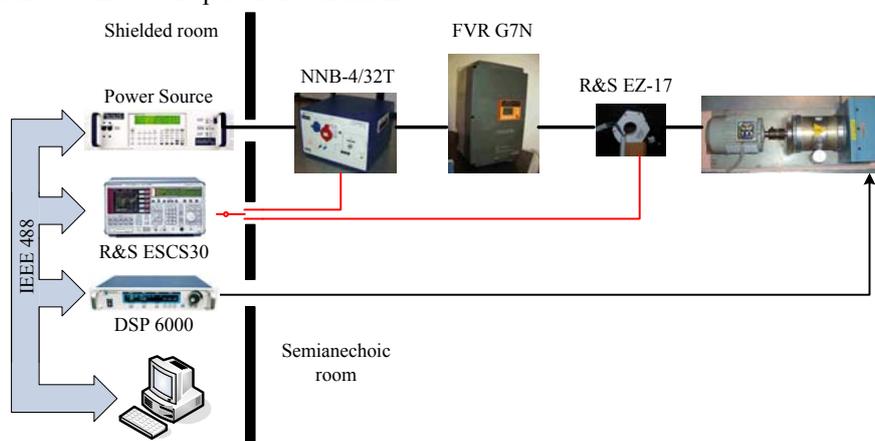


Figure 1 – Measurement setup

II. Experimental setup

Test	Torque [Nm]	Motor Frequency [Hz]	Asym. [%]	Voltage [V]
1	0	30	0	190
2	0	50	-5	220
3	0	70	5	250
4	1.75	30	-5	250
5	1.75	50	5	190
6	1.75	70	0	220
7	3.5	30	5	220
8	3.5	50	0	250
9	3.5	70	-5	190

Table 1 – Experimental plan

Figure 1 shows the experimental setup. The equipment under test (EUT) is a Fuji Electric 3 Φ PWM inverter, powered by a Pacific Power AMX3120 power source, and connected to a 1.1 kW 3 Φ asynchronous motor loaded by a Magtrol hysteresis brake remotely controlled by a Magtrol DSP 6000 so that torque can be applied to the motor. PWM's switching frequency is fixed at 10 kHz. Emissions on power network's end of the EUT have been measured through a V-LISN (Rolf Heine NNB-4/32T, hereafter LISN), while a current probe (R&S EZ-17, model 2, hereafter CP) has been used on motor's end. In both cases disturbances flowing on phase 1 have been measured. Sensing devices have been alternatively connected to an R&S ESCS30 EMI receiver through a calibrated cable with negligible attenuation. To compare LISN and CP data, it is necessary to convert CP measurements expressed as voltage back to the current value flowing in the cable and then again to the voltage drop that such current generates across a 50 Ω resistor, according to the following expression:

$$V_{eq} = V_{CP} + 20 \log(1/Z_T) + 20 \log 50 = V_{CP} + K_T + 34,$$

where V_{eq} is the equivalent voltage, V_{CP} is the CP's output voltage, K_T is the transduction factor. Experiments have been carried out in the semi-anechoic room and shielded room of the Department of Electrical Engineering of the University of Naples Federico II, Naples, Italy. The focus of the research is to determine variations in conducted emission due to torque, motor's working frequency, unbalance in power voltage due to a variation in phase 1 voltage, and voltage level on all three phases. Initially, test points have been so chosen: 0, 1.75, 3.5 Nm for torque; 30, 50 and 70 Hz for motor frequency; -5%, 0, +5% for voltage unbalance; and 190, 220, 250 V for voltage level.

A complete factorial experiment would require a total of 81 testing points. Additionally, emissions must be measured with quasi-peak (hereafter, QP) and average (AV) detector [3] and with the two different probes. The grand total is therefore 324 measurements, further increased to 972 by application of a repetition factor of 3 in order to estimate experimental variance at each testing point. With a QP

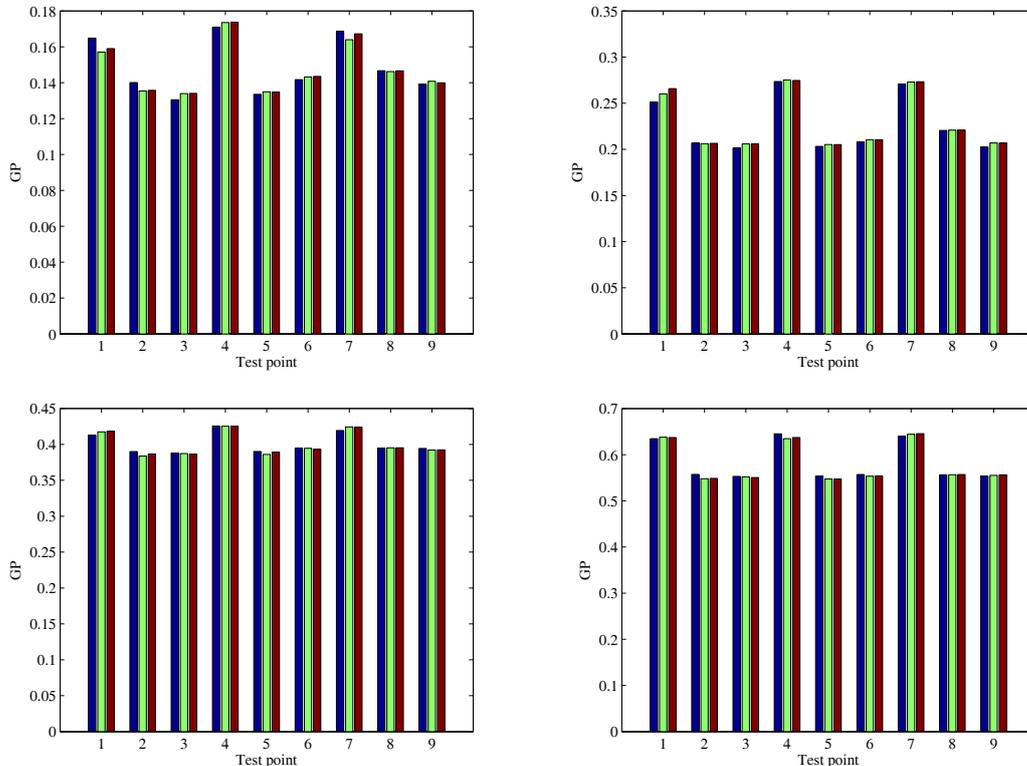


Figure 2 – GP measurements for QP (left) and AV (right) detector, with LISN (top) and CP (bottom) sensors

LISN QP			LISN AV		
Factor	<i>p</i> -value	Tukey	Factor	<i>p</i> -value	Tukey
T	4.46·10 ⁻⁷	1 ≠ 2 1 ≠ 3	T	5.44·10 ⁻⁶	1 ≠ 2 1 ≠ 3
F	1.11·10 ⁻¹⁶	1 ≠ 2 1 ≠ 3	F	0	1 ≠ 2 ≠ 3
A	2.6·10 ⁻⁵	1 ≠ 3 2 ≠ 3	A	0.16	ND
V	3.81·10 ⁻⁵	1 ≠ 2 1 ≠ 3	V	2.19·10 ⁻⁶	1 ≠ 2 ≠ 3
CP QP			CP AV		
Factor	<i>p</i> -value	Tukey	Factor	<i>p</i> -value	Tukey
T	1.1·10 ⁻⁶	1 ≠ 2 1 ≠ 3	T	8.7·10 ⁻³	1 ≠ 3 2 ≠ 3
F	0	1 ≠ 2 1 ≠ 3	F	0	1 ≠ 2 1 ≠ 3
A	0.03	1 ≠ 3	A	0.68	ND
V	7.25·10 ⁻³	1 ≠ 3	V	0.17	ND

Table 2 – Anova and multiple comparison tests' results

overcome of the limit respectively, where n is the total number of frequencies measured at each test point. We can now define a global index GP as: $GP = NX$ if $k = n$, that is if the EUT complies with emission limits at all frequencies; $GP = X$ if $l \geq 1$, that is if emissions are over the limits for at least one frequency.

III. Measurement results

Figure 2 shows results of GP measurements with AV and QP detector for both LISN and CP sensors. In all experiments, emissions overcame the limit because the EUT was not provided with an EMC filter, and therefore GP values are all positive. It is apparent that test points 1, 4 and 7, which are all characterized by the same PDS's working frequency, i.e. 30 Hz, generally show the highest values. An Analysis of Variance (ANOVA) performed on global parameter's values (see Table 2) confirms that motor's frequency is the parameter that influences conducted emissions most significantly, while the effect of an asymmetric power or a variation of power voltage seems to be quite dependent on the sensor and detector used. To determine which levels of the input parameters is most different from the others, a Tukey multiple comparison test, which resorts to the Studentized range distribution, has been carried out. Results are also shown in Table 2. As an example of the variations in the emissions' frequency content, Figure 3 shows measurements for the experiments at test points number 1, 2 and 3, for the LISN with AV measurements.

It must be noted however that the reduced plan doesn't allow to determine the joint effects of two or more factors, because of the inherent reduced resolution, but in one case, namely the AV measurements with CP, in which case the hypothesis of an interaction between torque and frequency turns out to have a p -value of 0.35, too large to decide positively for the alternative hypothesis that the interaction does

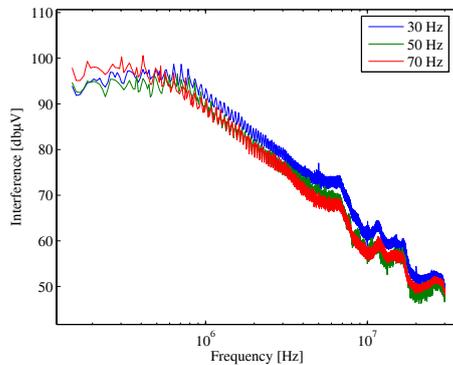


Figure 3 – Emission spectra for LISN measurements with AV detector under PDS's frequency variations

measurement taking some 45 minutes, and AV measurement taking 15 minutes, it is apparent that such a plan is unpractical, so a reduced plan based on an $L_9(3^4)$ orthogonal Taguchi matrix [9] has been chosen, thus decreasing the number of experimental points to 9 (shown in Table 1), for a grand total of 108 experiments. To determine if a variation in conducted emissions does occur, an index has been introduced that gives global knowledge of the behaviour of the emission spectrum in the frequency measurement range, and is strongly correlated to an overcome of standard limits.

Preliminary, let us define NX and X as the average distance between the measured voltage M_i and the corresponding limit L_i at the generic frequency, normalized to the limit L_i :

$$NX = \frac{1}{n} \sum_{i=1}^k \frac{M_i - L_i}{L_i}, \quad X = \frac{1}{n} \sum_{j=1}^l \frac{M_j - L_j}{L_j},$$

for the k frequencies for which there is no overcome and the l frequencies for which there is an

exist. To gain complete knowledge for all other cases, a complete factorial plan with only frequency and torque variations has been designed and executed. For the new experimental plan, while torque has been varied within the same levels as before, the frequency range has been reduced to obtain a better resolution of results. New experimental points are 30, 40 and 50 Hz, while power voltage is symmetric and at the nominal value. Results of GP measurements and Anova are shown in Figure 4 and Table 3. While the strong dependence on motor's working frequency is confirmed, it is apparent that variations in the load show much larger variations in GP measurement than in the preliminary study. One possible reason for that is that variations of power

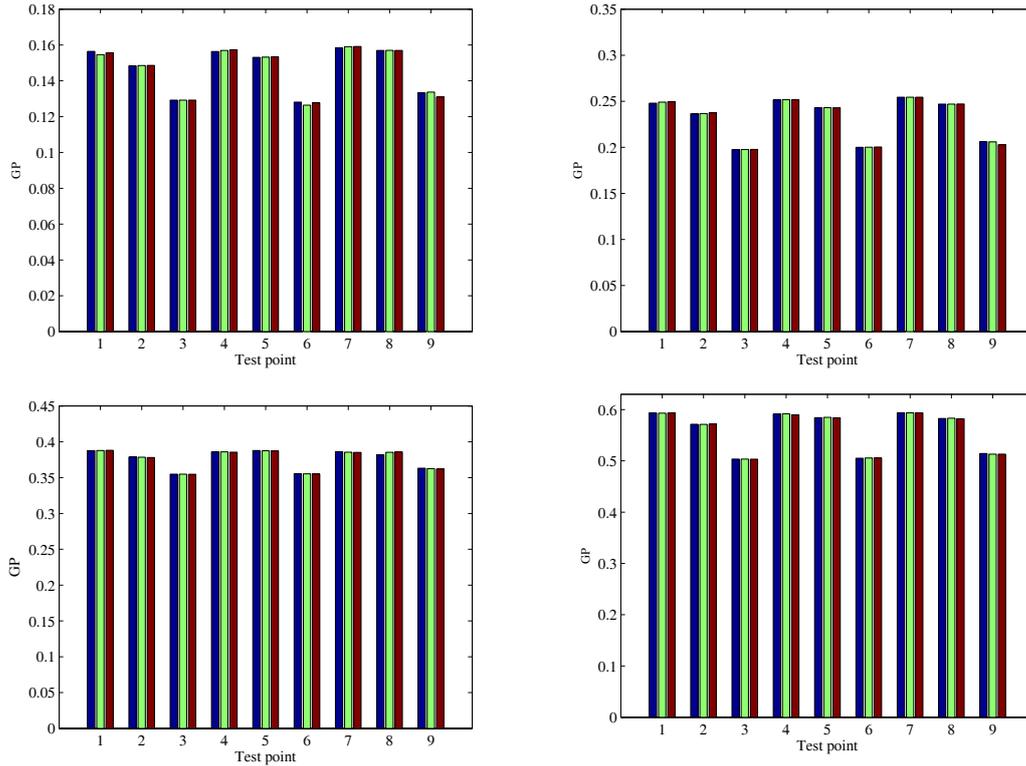


Figure 4 – GP measurements for QP (left) and AV (right) detector for LISN (top) and CP (bottom) sensors

voltage which were applied in the first phase of the research, that may have induced masking of the real impact of principal effects. Furthermore, a strong joint effect of factors can be observed in all four measurement configurations, which in some cases is even stronger than one main effect (see for example the CP with QP case). One more comment pertains the different p -values obtained for the CP with AV measurement, which in the second experimental campaign shows a strong joint effect of torque and frequency, which is in contrast with results obtained in the preliminary stage.

This discrepancy may be due to the different motor's frequency range that has been investigated. In Figure 5 the emission spectra of LISN and CP measurements with AV detector are shown for the three motor's frequencies with 0 Nm torque, together with the difference between the maximum and minimum measured value at each measurement frequency. The main difference is the dependence of uncertainty with frequency: in LISN measurements, differences between 2 dB and 7 dB show up in the high-frequency end, while in the low-frequency end they keep around 4 dB, as opposed to CP measurement which show a higher constant value of some 6 dB in the low-frequency end, and differences between 3.5 and 7 dB in the high-frequency end.

III. Conclusions

An investigation about uncertainty in conducted emissions measurements caused by different working

LISN QP		LISN AV	
Factor	p-value	Factor	p-value
L	$1.87 \cdot 10^{-11}$	L	$6.9 \cdot 10^{-14}$
F	0	F	0
L*F	$6.4 \cdot 10^{-7}$	L*F	$1.95 \cdot 10^{-4}$
CP QP		CP AV	
Factor	p-value	Factor	p-value
L	$3 \cdot 10^{-8}$	L	$6.66 \cdot 10^{-16}$
F	0	F	0
L*F	$7.5 \cdot 10^{-11}$	L*F	$6.2 \cdot 10^{-15}$

Table 3 – Anova results

conditions of a power drive system has been carried out. Experimental results demonstrate that some factors, like output frequency of the PDS and braking torque applied to motor, can cause relevant variations in emissions amplitude. Effects have also proven to depend on motor's frequency interval investigated, which also seems to affect the joint effect of torque and frequency itself. Future work will include testing of EUT's behaviour under the influence of other parameters or operating conditions, like stationary disturbances on power voltage (ie., flicker, harmonic and inter-harmonic components).

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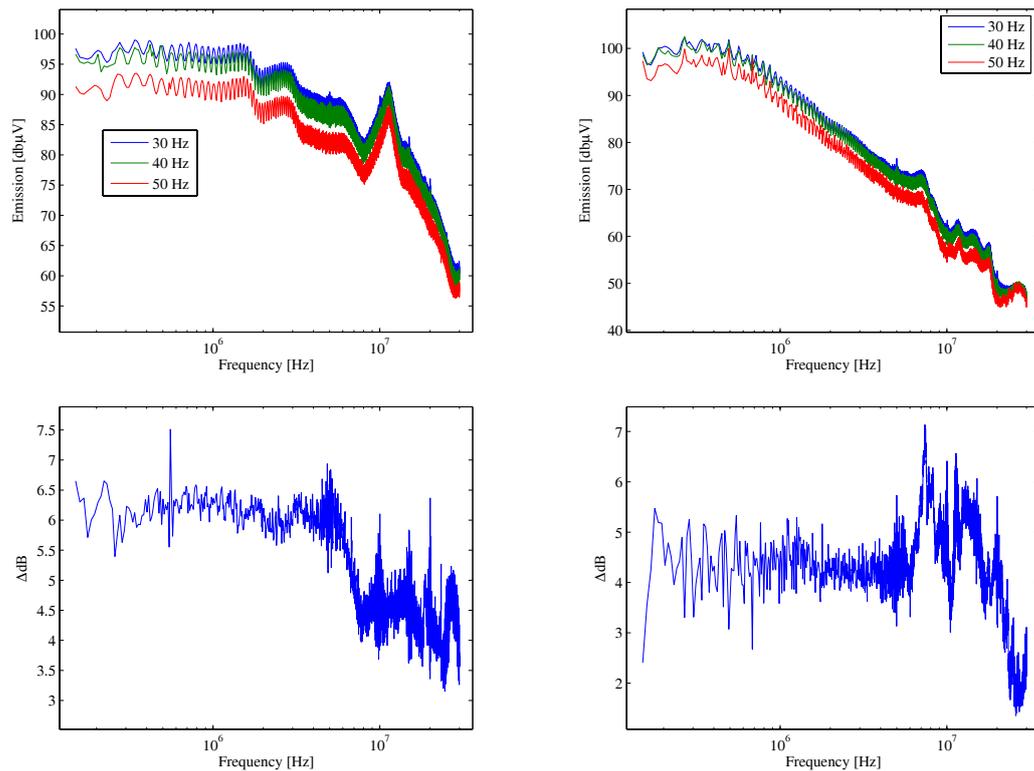


Figure 5 – Emission spectra (top) and differences (bottom) for AV measurements with LISN (right) and CP (left).

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