ADVANCED MEASUREMENT TECHNIQUES FOR POWER QUALITY ANALYSIS

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Abstract: The evaluation of the impact on power network quality of power electronic converter, such as inverter or adjustable speed drive requires the knowledge of quality indices and the setting-up of suitable measurement techniques for their evaluation.

In the paper, the authors firstly accomplish a description to the indices used for the electrical supply quality characterization; successively they describe an automatic measurement station designed for the evaluation of impact of power electronic equipment on the power quality; finally an original testing procedure, based on ANOVA and fractional factorial techniques, implemented to minimize the amount of measurements necessary to fully evaluate quality indices referred to the electromagnetic behavior of power electronic converters are presented.

Keywords: power quality, ANOVA, fractional factorial technique, power converter

1 INTRODUCTION

When utilizing electrical power it is necessary that plants with their equipment do not modify the quality of supplied energy. In industrial environment often coexist many equipment generating conducted and/or radiated disturbances such as power converter, variable speed drives (VSD) and devices such as computers, programmable logical controller (PLC's), communication’s systems, which could suffer momentary or permanent performance decrease due to the above mentioned disturbs [1,2].

Due to the importance of the problem, in the last years from a one hand it has been developed a deepened study on the parameters characterizing the quality of the electric energy, while from the other hand companies supplying electrical energy have stated severe limitations to the maximum of allowable disturbances induced on its network from the users.

It is then necessary the evaluation of impact of power electronic equipment on the power quality of electrical distribution network. It requires: i) to make references to indices that characterize the quality of the electrical energy; ii) to evaluate the power electronic equipment influence on such indices; iii) to perform the measurement of the most important electrical quantities that engraves on the indices value in various working conditions of the drive.

If on the one hand there is a trend to standardize tests that make the performances of various drives comparable, on the other hand the exigency is felt by the user to carry out the tests in conditions as similar as possible to the real operating conditions. For instance electromagnetic disturbances are often depending on the working operating conditions and on characteristics of the supplied energy, which can vary during the day for the cumulative effect of emissions of different type. As consequence, a suitable knowledge of the phenomena can be obtained carrying an exhaustive plan of tests in order to verify the immunity of the mains and of the most sensitive components in all issued disturbing situation. This involves performing a high number of tests with considerable costs and it is often difficult for Small and Medium Enterprises (SMEs) to carry out the requested experimental work. A solution that takes into account the exigency of saving experimental efforts may be based on the Experimental Design, techniques that allow testing costs and timesavings.

In the following, after a brief recall to the quality indices of the electric energy with particular reference to those influenced from electromagnetic pollution, the possibility to program an exhaustive plan of tests strongly reducing the number of necessary measures will be demonstrated.

The paper is completed with an example of evaluation of the electromagnetic performance of Variable Speed Drive in various operating working conditions obtained with the proposed tests design.

2 THE POWER QUALITY INDICES

The analysis of electrical power quality requires the comparison among the actual voltage and current waveforms and the ideal perfect sinusoids, which would determine the optimal behavior of the power system components. In practice, to make quantitative measurements, it is necessary to adopt quality indices that can be easily measured or obtained from the digital processing of the acquired data and to carry out a correlation analysis in order to evaluate occurrence and causes of the phenomena.

Digital processing of acquired quantities allows for the impact of harmonics on the power system evaluation; in particular the more usually adopted indices are [3-5]: i) The harmonic voltages and currents I content; ii) the voltage and current effective (RMS) values; iii) their crest factors (ratio of peak to rms); iv) the mean power; v) the fundamental frequency f_0; vi) the harmonic active power; vii) the conventional power factor; viii) the HD (Harmonic Distortion), defined as the ratio of the effective value of the distorted signal, from which the fundamental component is eliminated, to the effective value of the fundamental (V_0, I_0); ix) the THD (Total Harmonic Distortion), defined as the ratio of the effective value of the distorted signal, from which the fundamental component is eliminated, to the effective value of the original distorted signal; x) the conducted emission level [dBμV] in the range 0.15÷30 MHz.

For the estimation of the effects produced on a communication line, the susceptiveness of the circuit to the effects of inductive interference can by considered. Because the produced effects are not uniform over the audio-frequency spectrum, they are estimated at the maximum ear sensitivity, at about 800 Hz (CCITT) [6]. The response is psophometrically weighted to obtain the standard parameters: the EDV (Equivalent Disturbing Voltage) is a voltage at 800 Hz which, if applied to the power line, would cause the same interfering effect, to be experienced in a nearby telephone line, as does the voltage on the power line and its harmonics and the EDI (Equivalent Disturbing Current). In the following, for the analysis we adopt the current THD at low frequency and EMI emission level, in high frequency.

3 POWER QUALITY EVALUATION BASED ON DESIGN OF EXPERIMENTS

When testing for EMC of installed electrical machinery engineers typical run the stated test to observe conformity to the standards in all possible operating condition.

In particular in case of variable speed drives, both frequency and current amplitude and shape vary and therefore it is necessary to determine electromagnetic emission levels in the space of interest to the experiment.

In the examined case the area will be defined between minimum and maximum speed (ω) and torque (C) values and a typical test plan could consist in evaluating the effect of one parameters at a time, while holding constant the other.

With this procedure the interaction among the studied factors cannot be observed and the total required measurements is usually very high.

On the other hand, even if we would run tests with both factors at the same time, it would be impossible to make separation of any of the main factors effect.

An efficient test strategy which allows both to reduce the numbers of experiments with the same available information and to find possible correlation among ω, C and electromagnetic emissions, may be developed carrying out a analysis of variance test (ANOVA); furthermore a fractional factorial experiment which use only a portion of the total possible combinations to estimate the main factors effects and their interactions is performed [7,8].

In considered case study there are two controlled parameters in the experimental situation (torque and speed) and therefore we have to consider a two-way ANOVA.

We may evaluate in low frequency the THD and in high frequency the conducted electromagnetic emission; each one of them may be decomposed in: i) Emission due to torque factors (C); ii) Emission due to speed factor (ω); iii) Variation due to the interaction of factors C and μ; iv) Variation due to errors.

Indicating with n the total number of observations and with T the sum of all observations, the equation for total variation observed values may be written as:

$$SST = SSw + SSC + SSwC + SSE$$

where:

$$SSw = \sum_{j=1}^{c} \frac{x_j^2}{r \cdot n} - \frac{GT^2}{r \cdot c \cdot n} \qquad SSC = \sum_{i=1}^{r} \frac{x_i^2}{c \cdot n} - \frac{GT^2}{r \cdot c \cdot n}$$

are the variation due to speed and torque

$$SST = \sum_{i=1}^{r} \sum_{j=1}^{c} \sum_{k=1}^{n} x_{ijk}^2 - \frac{GT^2}{r \cdot c \cdot n}$$

is the total sums of squares (variation of all observations relative to zero);

$$SSwC = \sum_{i=1}^{r}\sum_{j=1}^{c} x_{ijk}^2 - \sum_{i=1}^{r}\frac{x_i^2}{c \cdot n} - \sum_{j=1}^{c}\frac{x_j^2}{r \cdot n} + \frac{GT^2}{r \cdot c \cdot n}$$ is the variation due to interaction of speed and torque factors;

$$SSE = SST - SSw - SSC - SSwC$$ is the variation due to error.

The meanings of the parameters reported in the previously analytical formulation are:

r	number of C factor levels,	c	number of ω factor levels,
n	number of samples for each observation	GT	cumulative sum of all observations,
x_i	sum of i-row for ω factor	x_j	sum of j-column for C factor,
x_{ij}	sum of value of observation ij,	x_{ijk}	value of k-th column ij.

Performing and plotting test data it's possible to observe not only the level of emissions in operating conditions but even if the interaction between ω and C will play a substantial part in determining emissions.

To compute the estimated response in any point in the system, a full experimental analysis can be performed by applying a multilevel multivariable experiment that allows to obtain requested data with a limited number of measurements; in particular, for a two variables analysis only 13 experimental observations at each emission frequency are sufficient to develop the EMC performance analysis of VSD instead of the 49 observations required from a one at a time test plan [9].

4 THE MEASUREMENT STATION

In order to evaluate the impact of VSD on network power quality a suited measurement station was set-up.

The implemented measurement station, reported in Fig. 1, is able to perform high precision power measurements on high efficiency variable speed drives and to verify the presence of EMC problems [10].

In particular it allows for the acquisition of high frequency data for an accurate measurement of previously defined quality indices, for the analysis of chopping signal and the collection of a suitable amount of data for the measurement of the lowest frequency harmonics and interharmonics. Moreover it allows the evaluation of electromagnetic pollution quantities [11].

The station exhibits a VXI-based Virtual Instrument linked to a Personal Computer via a standard interface. The signals acquisition has been performed by an high resolution VXI digitizer provided of 16 channels and a 16 bits A/D with maximum sample rate of 200 kS/s and record length of 64 kS, for each channel, for high accuracy power measurements and by a 12 bits high speed (20 MS/s) VXI digitizer for EMI analysis.

The mechanical load of the motor is realized by means of a hysteresis absorption brake. As the transduction and conditioning section is concerned, Hall-based current and voltage transducers with an accuracy of 0.1% on a bandwidth of 600 kHz, have been selected.

In particular, the measurement station, for each test point provides: i) efficiency determination of the whole drive and of each component under specified supply conditions; ii) verification of working stability over the whole speed regulation range; iii) voltage and currents line and motor input Total Harmonic Distortion THD; iv) determination of the conventional power factor and phase displacement between voltage and current fundamental harmonic in order to evaluate the impact of VSD on supply power network; v) measurement of conducted emission levels in the range 0.15÷5 MHz.

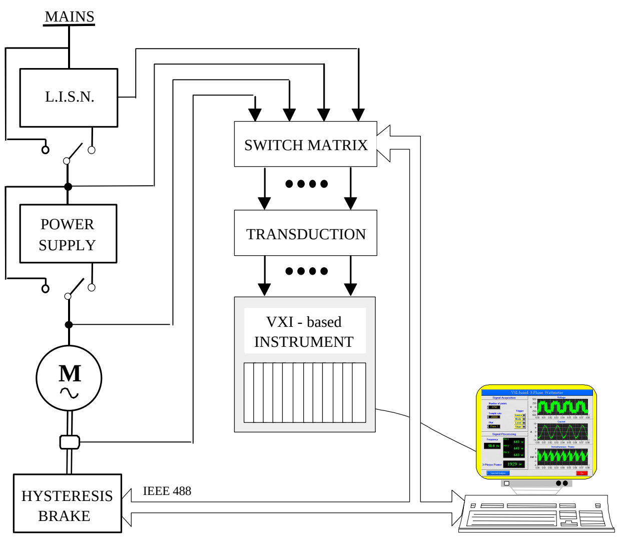

Figure 1. The measurement station.

5 EXPERIMENTAL RESULTS

With the aim to verify the proposed test program procedure, several experimental tests have been carried out on a low power electrical drive provided with a 3 kW asynchronous motor and a 5.5 kW IGBT Inverter; speed is spanning from 0 to 1500 rpm, torque from 0 to 7 Nm.

The acquired signals have been processed in order to evaluate the reported quality indexes and the emission level.

5.1 Low frequency power quality analysis

Several experimental tests have been performed on the electrical drive under test to determine the effects of speed and torque on the current harmonics contents.

In tab. 1 current THD vs. the torque and speed, used for two-way ANOVA analysis, measured in input of the VSD, are reported. Starting from the values in tab. 1, and applying the analytical formulation reported in § 3, the values summarized in tab. 2 have been obtained.

Variances have been calculated as follows:

$$S_w^2 = \frac{SSw}{c-1} = 450\,; \quad S_C^2 = \frac{SSC}{r-1} = 2312\,; \quad S_{wC}^2 = \frac{SSwC}{(r-1)(c-1)} = 60\,; \quad S_E^2 = \frac{SSE}{rc\,(n-1)} = 1.25$$

The F-statistic at α=0.005 level of confidence and at 1 degree of freedom of numerator and 4 degree of freedom of denominator results: $F_{.005,(1),(4)} = 31.33$

The dependence of parameters from speed and torque has been evaluated.

- Check if there exists dependence between THD_I and speed.

H_0: No THD_I variation due to factor ω

H_0 reject if: $F_{(1),(4)} = \frac{S_w^2}{S_E^2} = 360 > F_{.005,(1),(4)} = 31.33$

- Check if there exists dependence between THD_I and torque.

H_0: No THD_I variation due to factor C

H_0 reject if:

$$F_{(1),(4)} = \frac{S_C^2}{S_E^2} = 1849 > F_{.005,(1),(4)} = 31.33$$

- Check if there exists dependence between THD_I and the interaction of speed and torque.

H_0: No THD_I variation due to the interaction of factors ω and C

H_0 reject if: $F_{(1),(4)} = \frac{S_{\omega C}^2}{S_E^2} = 48 > F_{.005,(1),(4)} = 31.33$

The analysis of data processed by F-test shows that exists a considerable THD_I variation due to torque, lower variation on speed and on interaction between torque and speed.

5.2 High frequency EMI analysis

In the same way, several experimental tests have been performed in order to determine the effects of speed and torque on the high frequency emission level.

Table 1. Two-way ANOVA experimental data

THD_I [%]	w_1 900 rpm	w_2 1500 rpm	total
C_1 1 Nm	121 123	102 101	447
C_2 7 Nm	83 82	74 72	311
Total	409	349	758

Table 2. ANOVA Table

	Sum of squares	Degrees of freedom	Variance	Statistic F-test
ω	450	1	450	360
C	2312	1	2312	1849
ωC	60	1	60	48
E	5	4	1.25	
T	2827	7		

In tab. 3 the emission levels in dBμV vs. the torque and speed, used for two-way ANOVA analysis, are reported. Starting from the values in tab.3, and by proceeding in the same way of low frequency THD analysis, the values summarized in tab.4 have been obtained by applying the following formulae:

$$S^2_\omega = \frac{SS\omega}{c-1} = 0.032\ ;\quad S^2_C = \frac{SSC}{r-1} = 0.968\ ;$$

$$S^2_{\omega C} = \frac{SS\omega C}{(r-1)(c-1)} = 0.722\ ;\quad S^2_E = \frac{SSE}{rc\,(n-1)} = 0.00225$$

The F-statistic at α=0.005 level of confidence and at 1 degree of freedom of numerator and 16 degree of freedom of denominator results: $F_{.005,(1),(16)} = 10.58$

- Test on dependence between EMI and speed:

$$F_{(1),(16)} = \frac{S^2_\omega}{S^2_E} = 14 > F_{.005,(1),(16)} = 10.58$$

- Test on dependence between EMI and torque:

$$F_{(1),(16)} = \frac{S^2_C}{S^2_E} = 430 > F_{.005,(1),(16)} = 10.58$$

- Test on dependence between EMI and the interaction of speed and torque:

$$F_{(1),(16)} = \frac{S^2_{\omega C}}{S^2_E} = 321 > F_{.005,(1),(16)} = 10.58$$

Table 5. Design of experiments for VSD testing.

trial	w [rpm]	C [Nm]	$E_{1.5\ MHz}$ [dBmV]
1	988	1.88	82.3
2	1412	1.88	82.0
3	988	6.12	82.3
4	1412	6.12	82.6
5	900	4.00	82.7
6	1500	4.00	82.6
7	1200	1.00	81.7
8	1200	7.00	82.3
9	1200	4.00	82.0
10	1200	4.00	81.9
11	1200	4.00	81.8
12	1200	4.00	82.1
13	1200	4.00	82.2

The analysis of data processed by F-test has confirmed the consideration made for the low-frequency analysis. The processing of experimental data has evidenced a considerable EMI variation due to torque, lower variation on speed and on interaction between torque and speed.

Several experimental tests have been performed on the electrical drive under test, with the aim to obtain a high frequency EMC response surface map in the space of interest.

For the presented study, authors found very well suited to the problem use a central composite rotatable design with 13 trials, two multilevel variables (torque, speed), allowing: i) to compute the estimated response of emission levels versus each one of other parameters; ii) to generate a response surface map; iii) to make test of significance on each term in the regression equation. In tab.5 the design of the experiments and the experimental results, in the area 900 to 1500 rpm and 1 to 7 Nm are summarized. The response equation obtained can be used to compute the estimated response at any working condition of the Variable Speed Drive in order to evaluate its impact on supply network.

Table 3. Two-way ANOVA for HF EMI data

Emission [dBµV]	w_1 988 rpm	w_2 1412 rpm	total
C_1 1.88 Nm	82.3 82.3 82.4 82.3 82.3	81.9 81.8 81.9 81.9 81.8	820.9
C_2 6.12 Nm	82.4 82.4 82.3 82.4 82.4	82.6 82.7 82.7 82.7 82.7	825.3
Total	823.5	822.7	1646.2

Table 4. ANOVA Table

	Sum of squares	Degrees of freedom	Variance	Statistic F-test
ω	0.032	1	0.032	14
C	0.968	1	0.968	430
ωC	0.722	1	0.722	321
E	0.036	16	0.00225	
T	1.758	19		

As an example of powerful of proposed approach, in fig. 2 emission levels (referred to 1.5 MHz) vs. torque and speed is plotted. The system response evaluation is easier by referring to the generated emission level response-surface map, as shown in fig. 3.

6 CONCLUSIONS

Total Quality Management make more and more necessary to SMEs to develop test plans allowing the determination of the effects of numerous variables, each of one with many different values, on characteristics indices of products or on specific plant performances.

For this reason it is useful in SMEs to diffuse the use of modern experimental design techniques which allow a considerable experimental time and cost saving, without decreasing the quality

The experimental results show the power of the proposed approach and its characteristic to reduce the number of measurements and then cost and time spent for a fully evaluation of VSD impact on power quality network.

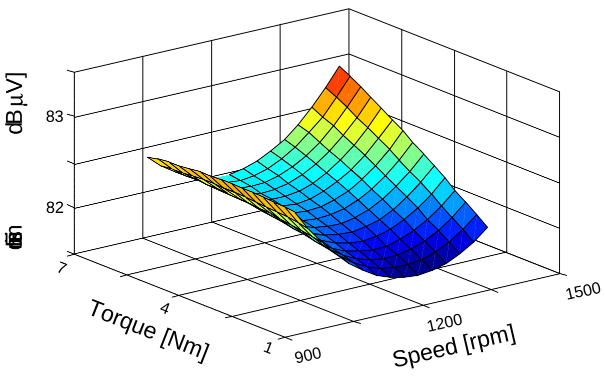

Figure 2. 1.5 MHz Emission level vs. torque and speed.

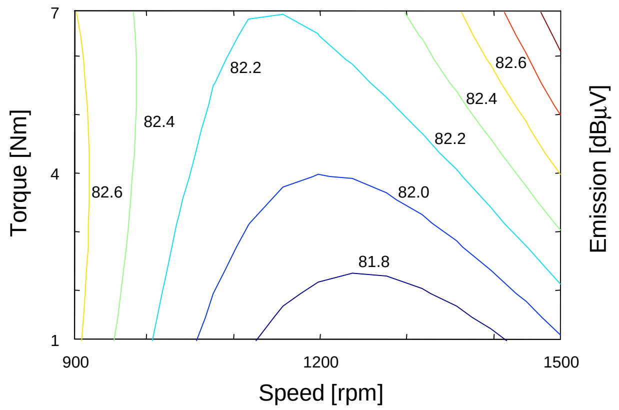

Figure 3. 1.5 MHz Emission level response-surface map.

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