Proc. of the 5th WSEAS/IASME Int. Conf. on Electric Power Systems, High Voltages, Electric Machines, Tenerife, Spain, December 16-18, 2005 (pp149-155)

On the Behavior of Induction Motors in Presence of Voltage Amplitude Modulations

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Abstract: – The voltage fluctuations of the electrical power supply and their effects on both industrial and domestic apparatuses are today a central topic of discussion. The aim of this paper is the evaluation of the effects of the low-frequency voltage amplitude modulation on induction motors, with both numerical and experimental analysis. For the numerical analysis different kinds of modulations have been considered, as suggested by the international committees; an experimental analysis has been applied to a three phase, 7.5 kW induction motor with the adoption of an ad hoc system for the EMC low-frequency immunity testing, with the adoption of rectangular amplitude modulations. The numerical and the experimental results show that a few percent amplitude modulations can involve a critical behavior in terms of torque. As for the light flicker effect measurement, a statistical approach can be adopted for the evaluation of the torque ripple, and a simplified relation can be used to relate the torque ripple to the measurement of the instantaneous voltage waveforms, without direct mechanical measurements.

Key-Words: - Power quality, voltage fluctuation, induction motors, electrical machines testing.

1 Introduction

The evaluation of Power Quality in low voltage systems requires the measurement of a wide set of parameters and indexes, for the characterization of different phenomena; high order harmonics, interharmonics, voltage fluctuations and high frequency disturbances with slew-rates of some microseconds or less can be mentioned as examples [1].
On detail, voltage fluctuations can involve a physiological irritating phenomenon, due to luminance fluctuations of the lighting (light flicker effect) [2]. The same voltage fluctuations that generate the flicker effect can produce undesired effects on other apparatuses, as motors, transforms and variable speed drives.
In this paper we consider the effect of the voltage amplitude modulations on three-phase induction motors, starting from the results obtained in the previous research activities about light flicker [3].
Specifically, our goals are: i) the numerical analysis of the behavior of induction motors in presence of different kinds of voltage fluctuations; ii) the implementation of a measurement and testing system for the experimental characterization of the induction motors performance in the described conditions; iii) the analysis of the numerical and experimental data, comparing the electrical and mechanical waveforms to evaluate the effects of the applied voltage modulations; iv) the synthesis and testing of a simplified model for the statistical evaluation of the torque ripple starting from measured voltage and current waveforms.

2 The Voltage Fluctuations

A wide set of voltage fluctuations can be adopted for the testing of the behavior of induction motors: i) sinusoidal amplitude modulations; ii) rectangular amplitude modulations; iii) over imposed interharmonic components; iv) "real world" fluctuactions. In the Power Quality measurement, the voltage amplitude modulations (Fig. 1) have been firstly considered, both with rectangular and sinusoidal shape: the IEC 61000-4-15 standard defines the testing procedure for the performance evaluation of the flicker meters applying both sinusoidal and rectangular amplitude modulation, in the frequency ranges 0.5-25 Hz. For this kind of modulations, the IEC requires an amplitude modulation measurement range of at least 10 % (20 % is suggested). The presence of interhamonic components on the mains is a well known phenomenon[4]; the effect of these components in terms of light flicker on fluorescent lamps and on the increasing of losses in electrical machines are known [5]. The "real world" fluctuations have been recently introduced by [6] for the evaluation of the performance of the light flicker meters in realistic conditions; the proposed amplitude modulations are not periodical and can be obtained as a sequence of different paths. Fig. 1 shows the first minute of the pattern 1; it consists of a sequence of rectangular amplitude modulation with variable duty cycle (10-30%), rate 1 Hz, with a 5 s rest period between each step; the other minutes are a similar repetition, with increasing rates (Table. I) of the described sequence.

Table I: Rates adopted in the pattern 1

Minute	1	2	3	4	5	6
Freq. [Hz]	1	2	4	8	10	15

The Fig.2 illustrates a sequence of the pattern 2; the amplitude of the modulations and the intermediate values are not defined yet.

Differently from the other modulating shapes and from interharmonics, it is difficult to analyze these “realistic” modulations with a fft-based approach.

All the described fluctuations can be adopted for the simulation of the voltage fluctuation when heavy loads as wood chipper, rolling mill and arc furnace are turned on, and to evaluate their effects on other electrical loads.

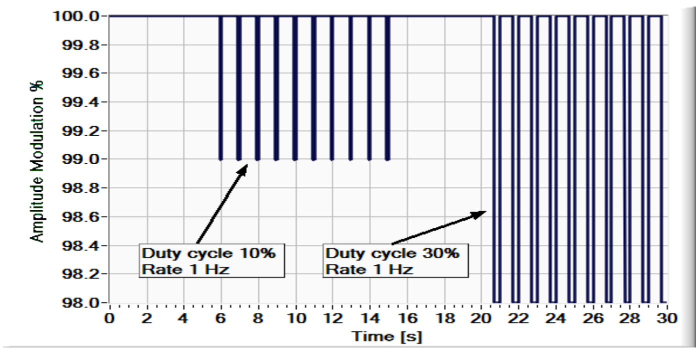

Fig.1 Realistic fluctuations: pattern 1, First 30 s sequence.

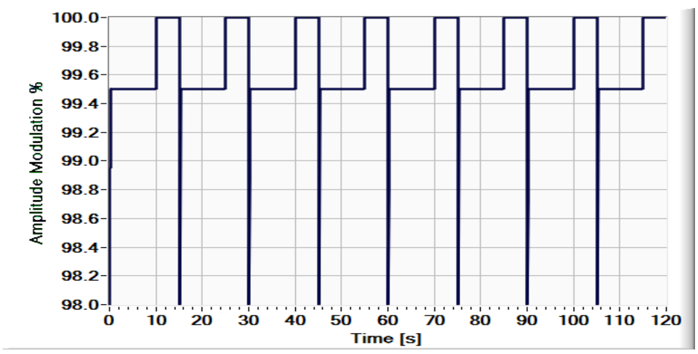

Fig.2 Realistic fluctuations: pattern 2, minutes 1-2 sequence.

3 The Effect of the Voltage Fluctuations on Induction Motors

On the mains, the voltage fluctuations usually happen simultaneously on each of the three phase voltage waveforms.

Each family of electrical apparatuses is characterized by different behavior in these conditions; we focused our interest on the induction motors, that in our country represent the majority of the low-voltage loads. Generally, the rapid variation of the voltage level can be considered as the cause of transitory phenomena, with fluctuations of electrical and mechanical quantities, and increasing of losses [7,8].On detail, the experimental application of three phase voltage waveform affected by amplitude modulations to an induction motor has shown the following important effects: i) torque ripples, ii) angular speed ripples, iii) vibrations transferred to the loads and to the supports; iv) acoustic noise. These phenomena can reduce the life of mechanical components as the bearings and the joints.

Moreover, in industrial applications, the described vibrations and torque ripples are not usually related to the probable presence of a modulation in the supply voltage waveforms, and the evaluation of the performance of induction motors in the described conditions is yet not considered and defined in the IEC standards.

4 A Numerical Analysis Based on a Dynamic Model

The evaluation of the effect of the voltage fluctuations can be performed both with numerical and experimental analyses; the choice of the numerical model should guarantee the correct evaluation of the transitory phenomena both on electrical and mechanical quantities.

A mathematical dynamic model of the machine, in terms of space vectors, making the usual simplifying assumptions (iron losses neglected, magnetic saturation neglected and so on), can be expressed as:

$$\frac{d\mathbf{i}_s}{dt} + k_s \frac{d\mathbf{i}_r}{dt} = \frac{\mathbf{v}}{L_t} - \alpha_s \mathbf{i}_s \tag{1}$$

$$k_r \frac{d\mathbf{i}_s}{dt} + \frac{d\mathbf{i}_r}{dt} = jk_r p\omega_r \mathbf{i}_s - (\alpha_r - jp\omega_r)\mathbf{i}_r \tag{2}$$

$$T(t) = \frac{3}{2} pL_m Im\left\{\mathbf{i}_s \hat{\mathbf{i}}_r\right\} \tag{3}$$

where $\mathbf{v}$, $\mathbf{i}_s$ and $\mathbf{i}_r$ are the space vectors of the supply voltage, of the stator current and of the rotor current referred to the stator respectively, T is the electromagnetic torque, ω_r is the mechanical rotating speed, the caret ^ denotes the complex conjugate operator and where:

$$\alpha_s = \frac{r_s}{l_s + L_m} \qquad \alpha_r = \frac{r'_r}{l'_r + L_m} \qquad k_s = \frac{L_m}{l_s + L_m}$$

$$k_r = \frac{L_m}{l'_r + L_m} \qquad L_t = l_s + L_m \tag{4}$$

with:

l'_r	rotor leakage inductance referred to the stator;
l_s	stator leakage inductance;
p	pole pairs;
r'_r	rotor resistance referred to the stator;
r_s	stator resistance;
L_m	magnetizing inductance.

The model of the whole electromechanical system is completed considering the mechanical equation:

$$T + T_L = J\frac{d\omega_r}{dt} + (D\omega_r + F) \qquad (5)$$

where T_L is load torque, J is the moment of inertia of the whole mechanical system and $(D\omega_r + F)$ is the friction torque. All the adopted parameters have been obtained with the experimental characterization (Table II) of the induction motor under test.

Table II Electrical and mechanical parameters adopted in the dynamic model

D [N·m·s]	0.0015	r_s [Ω]	0.55	r'_r [Ω]	0.65
F [N·m]	0.153	l_s [mH]	4	l'_r [mH]	4
J [kg·m^2]	0.042	l_m [mH]	103		

4.1 Numerical results obtained with the pattern 1

The pattern 1 [6] is a sequence of rectangular pulse trains, with increasing rates (Fig. 1); even if the applied max amplitude modulation is 2%, the effect on the torque is high. The results obtained applying the all pattern are presented in Tables III-VI.

Table III Pattern 1 input power statistical indexes

Minute	Mean Power [W]	Power Range [W]	Standard Deviation [W]
1	4941	1930	95
2	4941	1930	134
3	4943	1900	192
4	4944	1900	274
5	4944	2060	324
6	4945	1990	359

Table IV Pattern 1 output power statistical indexes

Minute	Mean Power [W]	Power Range [W]	Standard Deviation [W]
1	4609	1660	83
2	4609	1650	118
3	4608	1690	169
4	4608	1650	240
5	4608	1880	286
6	4608	1810	316

Table V Pattern 1 torque statistical indexes

Minute	Mean Torque [Nm]	Torque Range [Nm]	Standard Deviation [Nm]
1	30.0	10.9	0.5
2	30.0	10.8	0.8
3	30.0	11.1	1.1
4	30.0	10.8	1.6
5	30.0	**12.3**	1.9
6	30.0	11.9	2.1

Table VI Pattern 1 speed statistical indexes

Minute	Mean Speed [rpm]	Speed Range [rpm]	Standard Deviation [rpm]
1	1470	10	3
2	1469	10	3
3	1469	10	3
4	1469	9	3
5	1469	10	4
6	1468	19	4

4.2 Numerical results obtained with the pattern 2

The pattern 2 [6] is a sequence of 4 different modulating shapes.

In this case, an amplitude modulation of 4% generates a torque increasing up to 35 %.

The statistical indexes obtained applying the minutes 1-2 are reported in Tables VII-X.

The results obtained applying the modulation in the minutes 3-4 of the pattern 2 are very similar to results in the previous tables; the effect of the modulations in the minutes 5-6 and minutes 7-8 are negligible, due to the voltage low slew rates.

Table VII Patten 2, minutes 1-2 input power statistical indexes

Modulation amplitude %	Mean Power [W]	Power Range [W]	Standard Deviation [W]
1	4940	940	14
2	4941	1870	28
4	4941	3670	55

Table VIII Patten 2, minutes 1-2
output power statistical indexes

Modulation amplitude %	Mean Power [W]	Power Range [W]	Standard Deviation [W]
1	4609	830	12
2	4610	1640	24
4	4610	3230	49

Table IX Patten 2, minutes 1-2
torque statistical indexes

Modulation amplitude %	Mean Torque [Nm]	Torque Range [Nm]	Standard Deviation [Nm]
1	30.0	5.4	0.1
2	30.0	10.6	0.2
4	30.0	21.0	0.3

Table X Patten 2, minutes 1-2
speed statistical indexes

Modulation amplitude %	Mean Speed [rpm]	Speed Range [rpm]	Standard Deviation [rpm]
1	1470	10	0
2	1471	10	1
4	1470	19	1

4.3 Numerical results obtained with sinusoidal and rectangular modulations

The sinusoidal amplitude modulations [2] seem to be the less critical for the induction motors; the results show a torque increasing up to 7.7 % in the worst case. This behavior is due to the typical slow slew rate of the sinusoidal shapes. The situation is quite different for rectangular modulations [2]; the results are similar to the ones obtained for the pattern 1. The statistical results are in Tables XI-XIV.

Table XI Rectangular modulations
input power statistical indexes

Mod. Freq. [Hz]	Ampl. Mod %	Mean Power [W]	Power Range [W]	Standard Deviation [W]
1	1	4942	970	75
	2	4942	1950	151
	4	4944	3880	302
5	1	4944	990	168
	2	4946	1980	337
	4	4952	3960	672
10	1	4945	1050	232
	2	4948	2100	465
	4	4959	4190	930
15	1	4945	960	275
	2	4945	1920	5551
	4	4967	3850	1102

Table XII Rectangular modulations
output power statistical indexes

Mod. Freq. [Hz]	Ampl. Mod %	Mean Power [W]	Power Range [W]	Standard Deviation [W]
1	1	4609	840	66
	2	4609	1690	132
	4	4607	3380	265
5	1	4609	830	265
	2	4609	1670	295
	4	4609	3350	591
10	1	4609	890	203
	2	4609	1770	406
	4	4609	3540	812
15	1	4609	870	242
	2	4609	1740	484
	4	4609	3480	969

5 The Testing System and the Experimental Results

The voltage waveforms are supplied by the EMC PARTNER HARCS 1000 THREE PHASE SYSTEM. This apparatus has been developed for three phase harmonic immunity and emission testing. His power section is fed by three-phase power lines. It filters the input voltage waveforms, and it can add steady-state harmonic components, interharmonics and voltage fluctuations.

It performs the generation of both sinusoidal and rectangular modulated sinusoidal voltage waveforms in compliance with IEC 61000-4-15 standard, in the ranges 100-125 Vrms, 200-250 Vrms, with a three-phase power maximum value 12 kVA. As voltage generator it is characterized by short-cut impedance lower than 3 mΩ, and it has a Line Impedance Stabilization Network type 0.4 Ω + j 0.25 Ω at 50 Hz, according to IEC 61000-3-3.

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Table XIII Rectangular modulations torque statistical indexes

Mod. Freq. [Hz]	Ampl. Mod %	Mean Torque [Nm]	Torque Range [Nm]	Standard Deviation [Nm]
1	1	30.0	5.6	0.4
	2	30.0	11.1	0.9
	4	30.0	22.0	1.7
5	1	30.0	5.4	1.0
	2	30.0	10.9	1.9
	4	30.0	21.8	3.8
10	1	30.0	5.8	1.3
	2	30.0	11.5	2.7
	4	30.0	22.9	2.7
15	1	30.0	5.7	1.6
	2	30.0	11.4	3.1
	4	30.0	22.7	6.3

Table XIV Rectangular modulations speed statistical indexes

Mod. Freq. [Hz]	Ampl. Mod %	Mean Speed [rpm]	Speed Range [rpm]	Standard Deviation [rpm]
1	1	1470	10	1
	2	1470	10	2
	4	1466	29	5
5	1	1469	10	3
	2	1469	10	4
	4	1467	29	6
10	1	1469	10	4
	2	1467	10	5
	4	1466	29	6
15	1	1468	10	4
	2	1466	10	5
	4	1467	29	7

For the transduction of voltage waveforms, we adopted LEM LV 100-400 Hall effect closed loop transducers.
A Magtrol HD hysteresis brake dynamometer has been used; this apparatus has a controller unit that is connected to the host computer via IEE 488 bus.
The torque and speed are available as analog output voltage signals. On the same computer, the NI 6052E 16 bit DAQ board performs the A/D conversion of the voltage, current, torque and speed waveforms. For each testing step, 4000 samples at a sampling rate of 1000 sample/s have been acquired. Both the measurement software and the brake control software have been developed in the NI LabVIEW® environment [9,10]. After the preliminary numerical testing, an experimental characterization have been performed. The main goal aim of this second activity paper is the validation of the numerical results; moreover, an interesting prospective is to obtain a procedure for the first evaluation of the torque and speed ripples starting from the direct measurement of three phase voltage and current waveforms in industrial environments, during the normal operating conditions. With this aim we adopted the following steps: i) choice of the motor load in terms of mechanical power; ii) selection of the voltage modulation amplitudes and frequencies; iii) acquisition of the three phase voltage and current, torque and speed experimental waveforms; iv) numerical evaluation of the rms voltage and current waveforms, in order to simply the visualization of the amplitude modulations; v) numerical evaluation of the input and output power waveforms; vi) statistical evaluation of the obtained data. The main features of the induction motor under test are: i) 380 V, 16.7 A star-connected; ii) 7.5 kW; iii) 1443 rpm. The electrical and mechanical parameters of this motor have been measured and adopted in the previous numerical analysis. The time domain diagrams in Fig.s 3-8 show the effects of rectangular voltage modulations obtained with: i) load mean power of 4.6 kW; ii) input voltage amplitude modulation frequency of 5 Hz; iii) input voltage amplitude modulation of 5%; iv) rectangular amplitude modulations. In this case the torque and speed variations are respectively in the ranges 21.2-40.8 Nm and 1458-1470 rpm. For the tested motor, the input power waveform and the torque waveform are very similar.
As for the analysis of the numerical results, a statistical approach have been used. It has been preferred to the frequency domain analysis because the voltage amplitude fluctuations in realistic conditions are not periodic [6] and they can introduce spectral leakage. In Table XV the main input power statistical indexes obtained with different modulation parameters are reported. The max measured input power range reaches the 77.6 % of the mean value. The statistical indexes of the output power are shown in Table XVI. In the worst conditions, the output power range reaches the 66.5 % of the mean value.

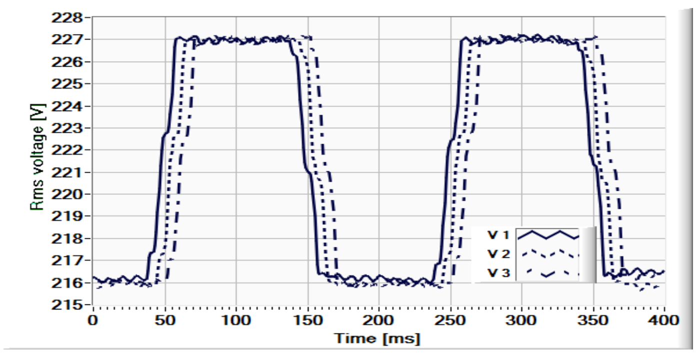

Fig.3 Voltage waveforms with 5 Hz, 5% rectangular amplitude modulation.

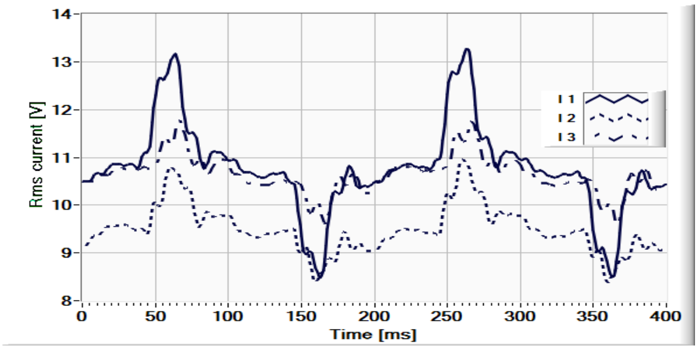

Fig.4 Three phase rms current waveforms

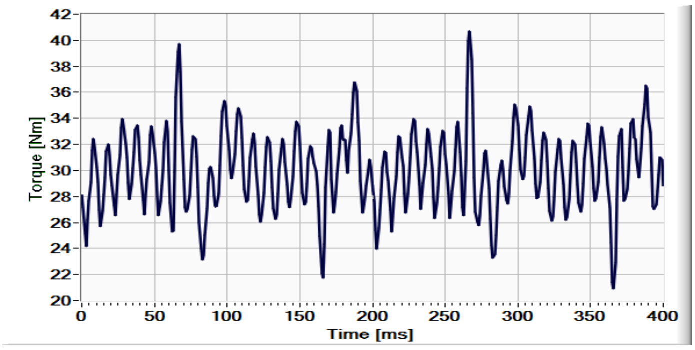

Fig.5 Torque waveform.

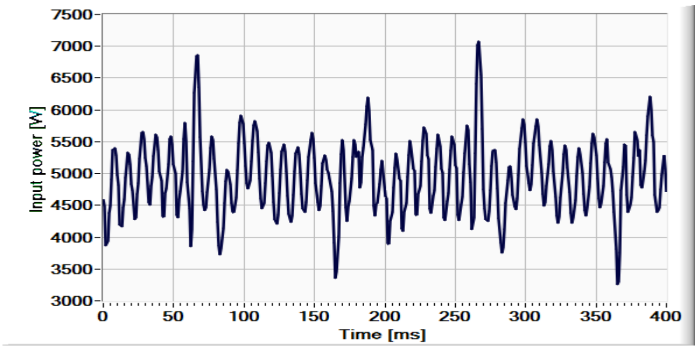

Fig.6 Total input power waveform.

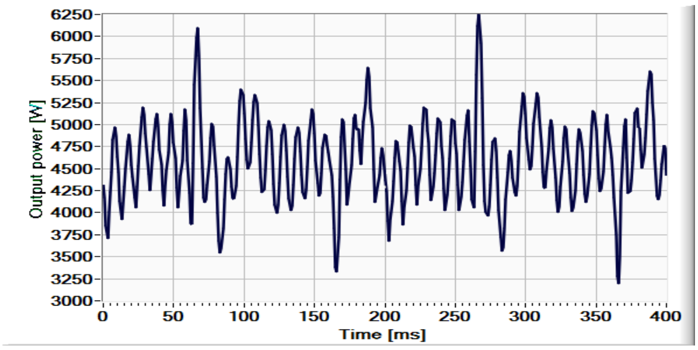

Fig.7 Output power waveform.

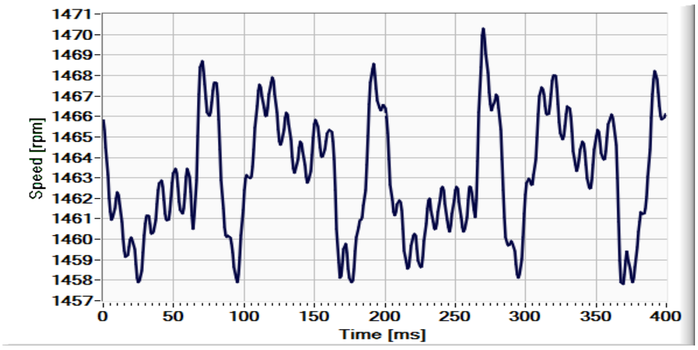

Fig.8 Speed waveform.

The most interesting effects involve the torque; the torque range is from 24.6 % up to 63.9 % of the measured mean torque (Table XVII).
This phenomenon can involve an unacceptable increasing of torsional stress in the couplings and vibrations.
It can be seen that the speed ripples obtained with the system under test are not very significant (Table XVIII). It is due to the value of the overall moment of inertia.
The problem of undesirable speed ripples would be more critical with lower power induction motors. Starting from the previous diagrams, it can be seen that the input power and torque waveforms are proportional, because of the small speed ripples.

TABLE XV. Input power statistical indexes

Mod. Freq. [Hz]	Ampl. Mod %	Mean Power [W]	Power Range [W]	Standard Deviation [W]
1	1	4942	1758	437
	5	4944	3668	475
5	1	4951	1945	427
	5	4951	3842	576
10	1	4943	1407	371
	5	4953	2860	552

TABLE XVI. Output power statistical indexes

Mod. Freq. [Hz]	Ampl. Mod %	Mean Power [W]	Power range [W]	Standard Deviation [W]
1	1	4595	1448	345
	5	4596	2897	376
5	1	4595	1544	336
	5	4597	3059	465
10	1	4597	1146	297
	5	4599	2197	437

TABLE XVII Torque statistical indexes

Mod. Freq. [Hz]	Ampl. Mod %	Mean Torque [Nm]	Torque range [Nm]	Standard Deviation [Nm]
1	1	30.0	9.5	2.3
	5	30.1	18.8	2.5
5	1	29.9	14.1	2.2
	5	29.9	19.1	3.0
10	1	30.0	7.4	1.9
	5	30.0	14.3	2.9

TABLE XVIII. Speed statistical indexes

Mod. Freq. [Hz]	Ampl. Mod %	Mean Speed [rpm]	Speed range [rpm]	Standard Deviation [rpm]
1	1	1462	6	1
	5	1463	15	3
5	1	1463	5	1
	5	1462	13	3
10	1	1463	4	1
	5	1463	9	2

These results confirm that input power fluctuations mainly produce torque ripples because of the smaller speed and storage magnetic energy fluctuations in the system under test.

6 Conclusions

The voltage fluctuations and modulations in low voltage feeders can involve undesirable effects on induction motors. The most important are torque and speed ripples that can generate vibration, noise and mechanical stress in the bearings, couplings and supports. Today, these phenomena are not defined in IEC standards, and it is difficult to relate the torque ripple to the voltage fluctuation in many industrial environments. The aim of this paper is the evaluation of these effects with both numerical and experimental analysis of the behavior of an induction motor, with the application of a three phase voltage waveforms affected by different kinds of amplitude fluctuations. A statistical approach has been proposed and adopted for the analysis of the acquired data. The obtained diagrams suggest the comparison between the input power and the torque waveforms. This approach can suggest interesting testing applications, because from the measurement of the instantaneous voltage waveforms, with a dynamic model of the motor, it is possible to identify a simplified relation for the torque ripple evaluations, without direct mechanical measurements.

7 Acknowledgement

This work was supported by Italian Ministry for University and Scientific and Technologic Research, under the grant “Cluster 13”, Project 7, at the Department of Electrical and Information Engineering, University of L’Aquila.

References

[1] EN 50160 – Voltage characteristics of electricity supplied by public distribution systems. 2000.

[2] EN 61000-4-15, Flickermeter – Functional and design specifications. 1999-04.

[3] G. Bucci, E. Fiorucci, D. Gallo, C. Landi, “Comparison among Traditional and New Digital Instruments for the Measurement of the Light Flicker Effect ” 2003 IEEE Instrumentation and Measurement Technology Conference, Vail, CO,USA May 20-22, 2003.

[4] Testa, A.; Gallo, D.; Langella, R. “Interharmonic measurements in IEC standard framework” Power Engineering Society Summer Meeting, 2002 IEEE Volume 2, 2002 Page(s):935 - 940 vol.2

[5] Emanuel, A.E. “Estimating the Effects of Harmonic Voltage Fluctuations on the Temperature Rise of Squirrel-Cage Motors” Power Engineering Review, IEEE Volume 11, Issue 3, March 1991

[6] CIGRE 36.05/CIRED WG 2/UIRPQ Joint Working Group CCU2 on Voltage Quality ”Test Protocol of IEC Flickermeter use in power systems voltage monitoring”, Draft 11, July 2004.

[7] C. A. G. Medeiros, J. C. de Oliveira, “ Effects of Voltage Fluctuations Associated to Flicker Limits on Equipments Performance” IEEE ICHQP Rio De Janeiro, October, 6-9 2002

[8] Ran Cao, E. R. Collins, “The Effects of Load Types on the Behavior of AC Motor Drives during Voltage Sags.” IEEE ICHQP Rio De Janeiro, October, 6-9 2002

[9] G. Bucci, E. Fiorucci, C. Landi ”State of the Art and Future Trends of Measurements techniques for Asynchronous Motor Characterization.” IEEE SDEMPED ’01 3rd IEEE International Symposium on Diagnostic for Electric Machines, Power Electronics and Drives. Gorizia, September 1-3, 2001.

[10] G. Bucci, E. Fiorucci, A. Ometto N. Rotondale “The Evaluation of the Effects of the voltage amplitude fluctuations on induction motors” Proceedings of IEEE Powertech 2005, June 27-30 St. Petersburg, Russia.