EXPERIMENTAL HARMONIC SPECTRUM ASSESSMENT OF A MODERN SINGLE-PHASE VARIABLE FREQUENCY DRIVE DESIGNED FOR SUPPLYING THREE-PHASE ASYNCHRONOUS MOTORS

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In this paper, an experimental model built for studying the impact of modern variable speed drives upon classical three-phase asynchronous motors, with a focus on the assessment of the harmonic generation, is presented. For this purpose, a series of experimental measurements have been elaborated by the authors, concerning main power quality parameters, total harmonic distortion level and their spectrum at different operating frequencies. The experimental results confirm the presence of the harmonics in the sine wave sinusoidal forms of voltage and current and raise a series of questions about the net performance of this operating ensemble in low voltage applications.

Keywords: experimental model, single-phase variable frequency drives, asynchronous motors, total harmonic distortion level

1. Introduction

Three-phase asynchronous motors are present in more than 70% of the current industrial applications, being used in almost all water recirculation loops and classical air ventilation systems [1], [16]. Most of these consecrated motors were specially designed and built for particular operating processes and have more than several decades of continuous operation, thanks to proven reliability and their systems dependability to be driven by specific operating parameters. [2]

The evolution of technology allowed the industrial sector to use this type of motors in a wider frame, by varying the rated nominal speed proportionally with the supplying voltage frequency, although they were initially designed to be operated constantly at nominal speed. [3] Thanks to the emergence of the variable-frequency drives (VFD) technology, almost all three-phase alternative current (AC) asynchronous motors can now be driven according to necessary load, from 0 rpm to nominal speed with high precision and no starting peak currents, thus allowing the operating system to be very efficient and extremely cost effective. [4]

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But what is the meaning of this interposing upon the quality of the supplied energy parameters? Could this “*energy saving*” solution affect in any way the proper functioning of these classic type of motors? What is the true impact of the AC-DC-AC transformation upon the quality of an electrical supply power system? To be able to answer as precisely as possible to these above questions, particular experimental conditions must be created, in order to simulate and monitor in real time the entire ensemble performance and the energy quality parameters. Therefore, in this paper an experimental model built for studying the impact of the modern single-phase variable frequency drives on three-phase asynchronous motors is presented. Using state-of-the-art measuring equipment the authors are investigating this impact, by collecting, monitoring and interpreting the quality of the parameters and also recommending adequate corrective methods [15] [18] for the generated harmonic spectrum of the ensemble.

2. Theoretical Background

Variable frequency drives, as similar with any other equipment converting an alternative voltage into a continuous voltage, are prone to generate harmonic levels into the supply power system, especially current harmonics. Motors fed by this type of equipment are not an exception, being also subject to a voltage and current harmonic level, especially when operating at levels above the rated 50 Hz frequency [10]. To have a clear overview of this phenomena, in this paper, it is envisaged by the measurement and the assessment of their spectrum. The measurements are elaborated both downstream of the static frequency converter (at the motor terminals) and in upstream of the static frequency converter (upon the power supply system).

The aim of the experimental measurements is the determination of the energy quality parameters, in order to monitor and the harmonic level assessment generated by the nominal operation of the variable speed drive – motor ensemble. The harmonics represent multiples of the 50 Hz fundamental and cause the distortion of the current and voltage sinusoidal waveform by summing them. Current harmonics are determined by the non-linear loads connected to the supply power system, in our case the variable frequency drive, the current drawn not having the same waveform as the supply voltage. The current harmonic level transferred through the system impedance determines voltage harmonics which distorts the supply voltage. The specific parameter to assess this level of harmonics in the alternating signal is called the total harmonic distortion factor *THD* and is associated with both current and voltage distortion:

- THD_u: voltage total distortion factor, associated at the installation level;
- THD_i: current total distortion factor, associated with non-linear components [9].

In the following sections, experimental determination of the quality of energy indicators, including total harmonic distortion factor THD, will be emphasized.

3. Experimental model

The experimental model is composed by three main parts: the mechanical structure, the measuring and data acquisition system and the control and command system. The mechanical part is represented by the asynchronous three-phase motor, squirreled cage AC induction type, and a secondary servo motor type and a DC generator whose role is to create the nominal torque for the AC motor by varying a load resistance. Both motors are connected by a shaft trapezoidal belt transmission. The measuring and data acquisition system is represented by the upstream Power Meter [5] and the downstream three-phase Power Quality Analyzer [6] for analyzing the electrical parameters spectrum. Both measuring equipments use current transformers and voltage probes for parameters value acquisition. The control and command system is represented by VFD operator console [7] and the computerized software [8] installed on a workstation. Fig. 1 is presenting the synthesized block diagram of the experimental model.

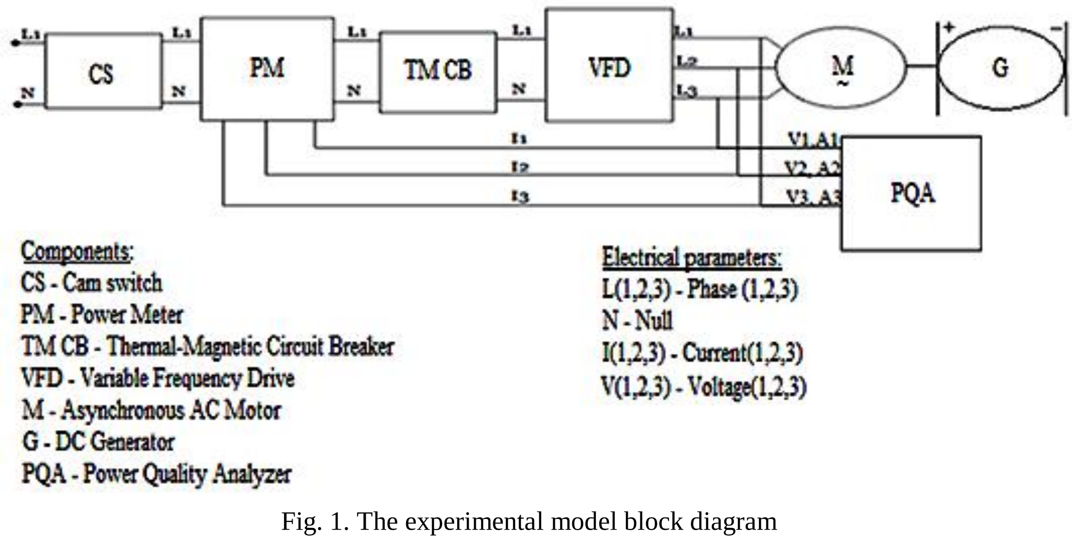


Fig. 1. The experimental model block diagram

The electrical schematic diagram of the elaborated experimental model is presented in Fig. 2.

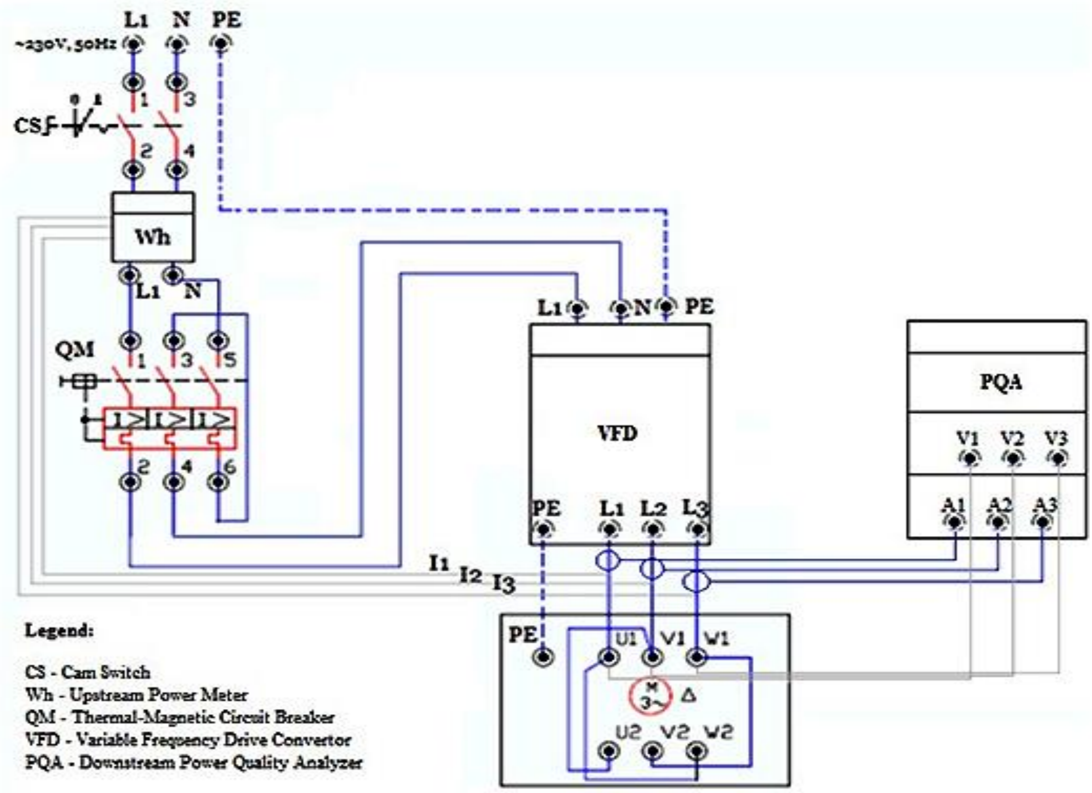


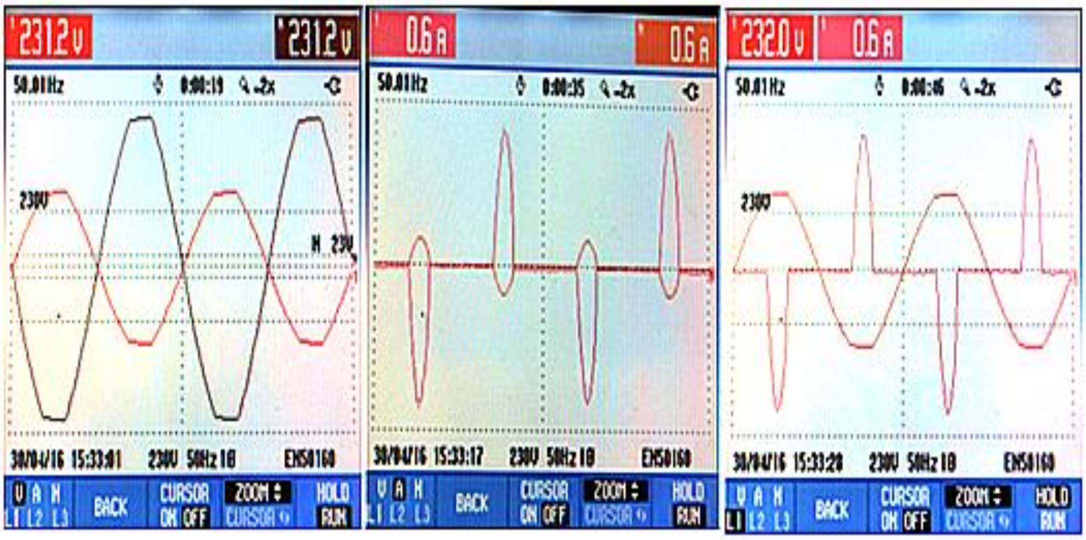
Fig. 2. The electrical schematic diagram of the elaborated experimental model

4. Experimental results

a) Experimental determination of the quality of energy indicators on the upstream of the static frequency convertor

The power supply system is characterized as being a pure sine wave single-phase 230 VAC network with a relatively low harmonic level, ranging in the limits (<5%) imposed by the effectual Standard [11] legislation.

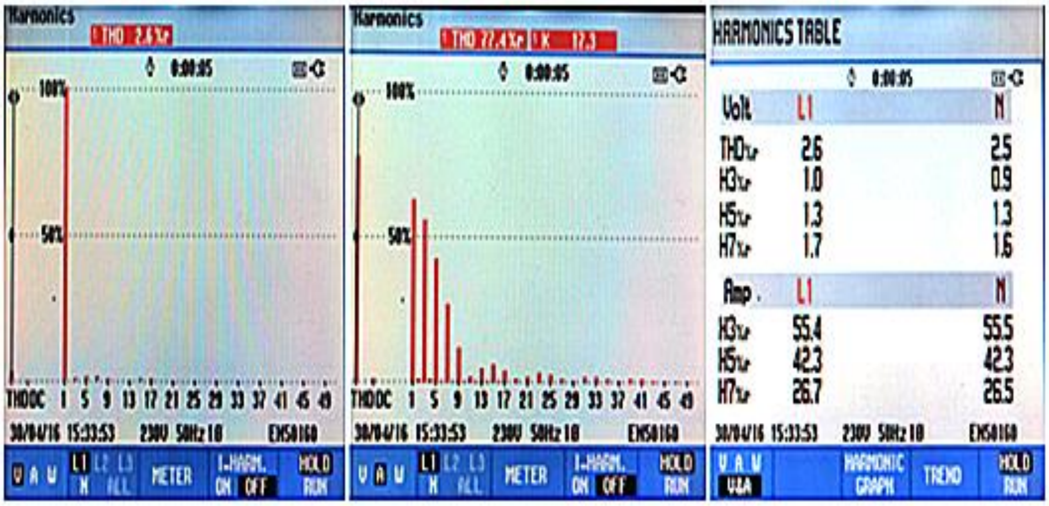
By supplying the experimental model at rated 50 Hz frequency, the voltage sine wave form remains relatively the same as the supply form, but the current sine wave is highly distorted due to non-linear characterization of the VFD. Fig. 3 is presenting their sinusoidal spectrum.



a) b) c)

Fig. 3. Voltage (a), current (b) wave form and the power supply line L1spectrum (c), operating at rated 50 Hz frequency

In order to determine the harmonic level, both voltage and current harmonic spectrums have been captured, as total distortion factor $THD_{U,I}$. In Fig 4, it can be observed that the THD_U level is relatively low, with only 2,6% of the fundamental (*r*), while THD_I is very high, ranging at almost 77,5%*r*. In Fig. 4c their distribution under tabular form, according to odd harmonic rank is presented.



a) b) c)

Fig. 4. Voltage (a), current (b) harmonic spectrum and $THD_{U,I}$ level (c) operating at rated 50 Hz frequency

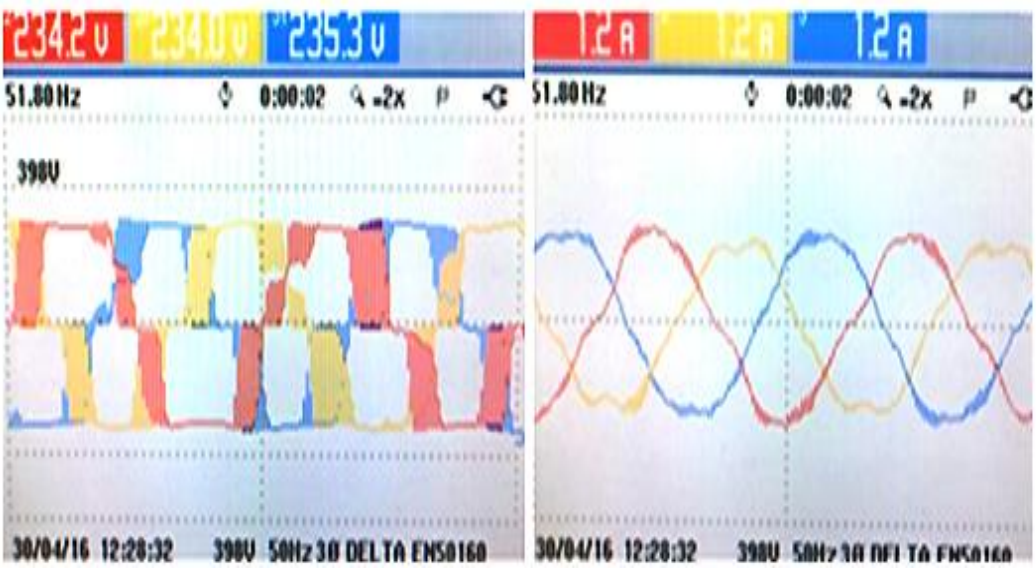
In order to determine the system powers, the phasors, the power factor (PF) and its inclusion in the *PQ* coordinate system, it must be firstly mentioned that the load of an AC electrical system has main two components: a resistive factor and a reactive factor, which can be inductive or capacitive. Resistive loads absorb active power (P) and reactive loads absorb reactive power (Q) from the power supply system. Apparent power (S) is calculated as being the vectorial sum of the active and reactive powers:

$$S = \sqrt{P^2 + Q^2 + D^2}$$

b) Experimental determination of the quality of energy indicators on the downstream of the static frequency convertor

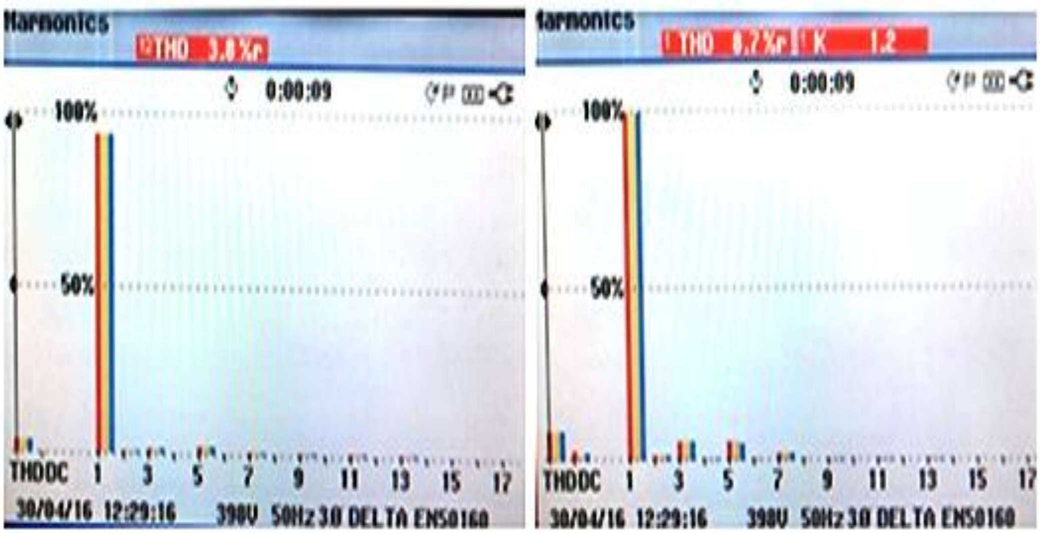
The VFD is characterized by a single-phase 230 VAC power supply, which uses a 6 diodes pulses rectifier bridge without any intermediary filtering circuit on DC bus. The built-in inverter generates three AC phases, with the same 230 V voltage per phase, but variable by amplitude and frequency.

With the asynchronous motor at rated parameters (torque and current using the DC generator as load) the electrical parameters at different voltage frequency have been determined experimentally. In Fig. 5, the wave form U and I spectrums at rated 50 Hz frequency on the AC motor terminals can be observed.



a) b)

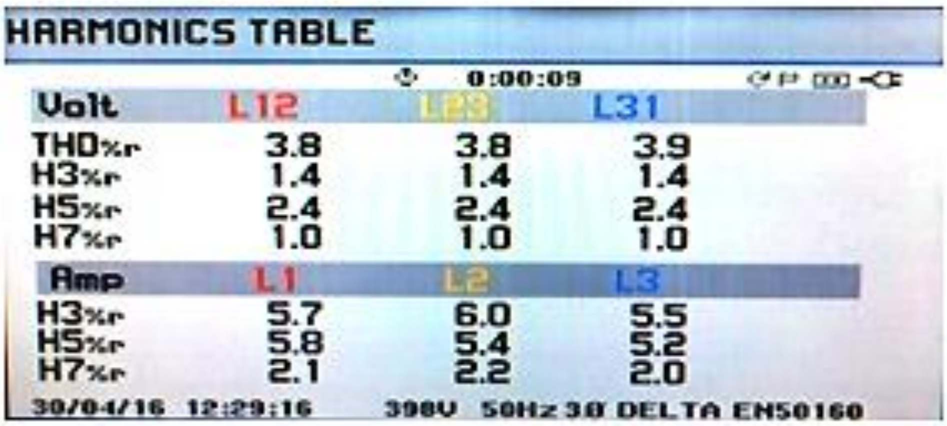
Fig. 5. U (a) and I (b) wave forms at rated AC motor parameters (50 Hz)



a) b)

Fig. 6.U (a) and I (b) harmonic spectrums at rated AC motor parameters (50 Hz)

From capture a1), it can be observed that all three voltage waveforms are width modulated, using Pulse Width Modulation (PWM) control technology. The sine wave forms follow the trajectory of a sinusoidal sine wave and are composed by pulses and generated by the IGBT type thyristors switching of the DC/AC inverter side. At nominal current and torque, the motor absorbs a relative sinusoidal current, with a THD_I level of 8,7%*r*. This relatively low harmonic level determines a consequent THD_U level, consisting in a level of 3,8%*r* (Fig.6). In Fig. 7, the *THD* distribution is presented in tabular form, taking into consideration the odd harmonic rank.



HARMONICS TABLE

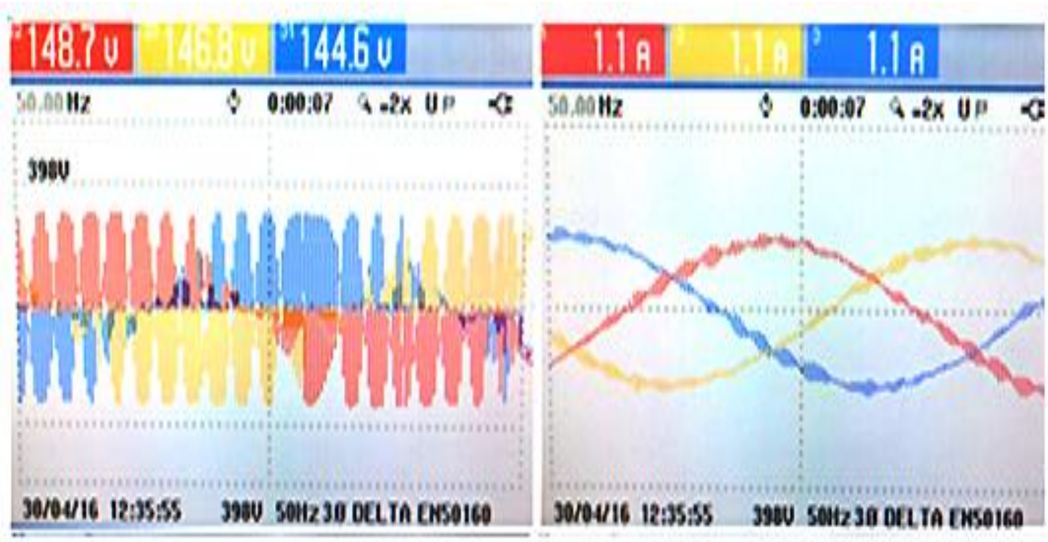
0:00:09

Volt	L12	L23	L31
THD%r	3.8	3.8	3.9
H3%r	1.4	1.4	1.4
H5%r	2.4	2.4	2.4
H7%r	1.0	1.0	1.0
Amp	**L1**	**L2**	**L3**
H3%r	5.7	6.0	5.5
H5%r	5.8	5.4	5.2
H7%r	2.1	2.2	2.0

30/04/16 12:29:16 390V 50Hz 3Ø DELTA EN50160

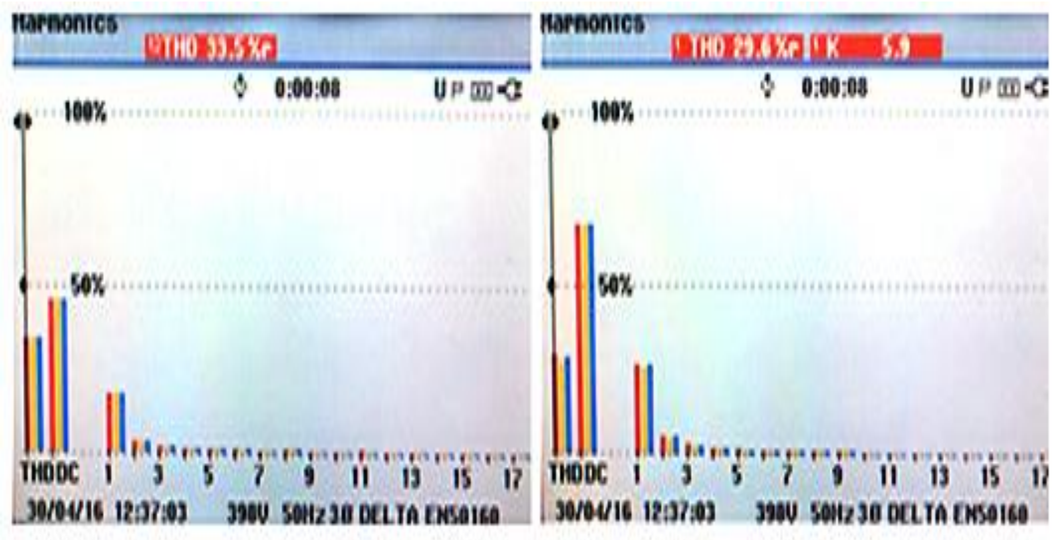
Fig. 7. $THD_{U,I}$ at the motor terminals on rated 50 Hz supply frequency

For operating frequencies below, the rated 50 Hz frequency, the VFD supplies the asynchronous AC motor with *U/f* ratio, the harmonic level of voltage and current increasing up to 10 times on *U* and almost 4 times on *I*. Fig. 8 illustrates the wave forms for *U* and *I* and Fig. 9 their harmonic spectrums at 20 Hz supply frequency at the AC motor terminals. Fig. 10 presents as table form the $THD_{U,I}$ distribution, taking into consideration the odd harmonic rank.



a) b)

Fig. 8. U (a) and I (b) wave forms at 20 Hz frequency supply at the motor terminals



a) b)

Fig. 9. U (a) and I (b) harmonic spectrums at rated AC motor parameters (50 Hz)

HARMONICS TABLE

0:00:08

Volt	L12	L23	L31
THD%r	33.5	33.6	34.1
H3%r	2.0	2.0	2.1
H5%r	1.2	1.2	1.2
H7%r	1.0	1.0	1.0
Amp	**L1**	**L2**	**L3**
H3%r	3.3	3.0	3.0
H5%r	1.8	1.7	1.7
H7%r	1.3	1.2	1.3

30/04/16 12:37:03 398V 50Hz 3Ø DELTA EN50160

Fig. 10. $THD_{U,I}$ at the motor terminals at 20 Hz supply frequency

For operating frequencies above the rated 50 Hz frequency, the VFD supplies the asynchronous AC motor with the same *U/f* ratio, but the harmonic level of voltage and current becomes even higher than the below rated nominal operation, taking values up to 11 times on *U* and almost 9 times on *I*. Fig. 11 illustrates the wave form of *U* and *I* and Fig. 12 their harmonic spectrums at 60 Hz frequency on the AC motor terminals. Fig. 13 presents as table form the $THD_{U,I}$ distribution, taking into consideration the odd harmonic rank.

a) b)

Fig. 11. U (a) and I (b) wave forms at 60 Hz frequency supply at the motor terminals

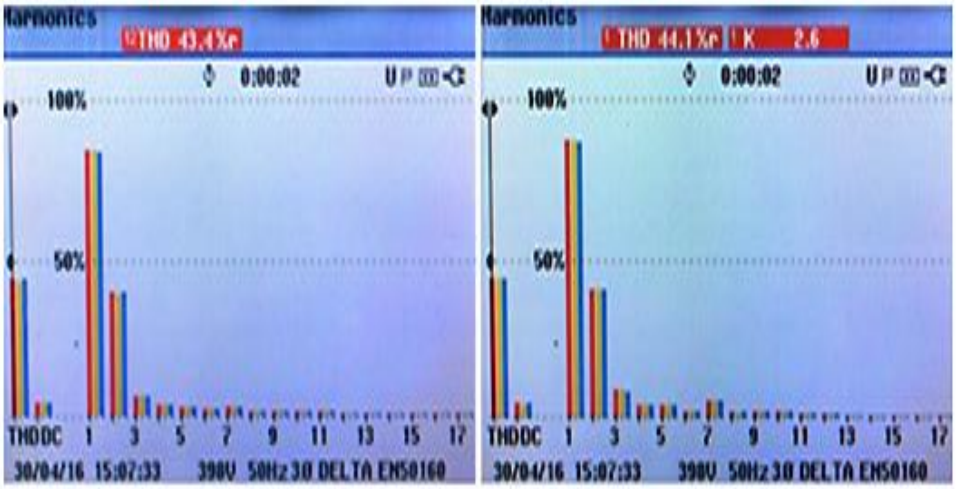


Fig. 12. U (a) and I (b) harmonic spectrums at rated AC motor parameters (60 Hz)

HARMONICS TABLE

0:00:02

Volt	L12	L23	L31
THD%r	43.4	43.3	43.6
H3%r	6.3	6.1	6.4
H5%r	2.9	2.8	2.9
H7%r	3.0	2.9	3.0
Amp	**L1**	**L2**	**L3**
H3%r	8.9	8.9	8.8
H5%r	4.0	4.3	4.2
H7%r	6.0	5.7	5.5

30/04/16 15:07:33 398V 50Hz 3Ø DELTA EN50160

Fig. 13. $THD_{U,I}$ at the motor terminals at 60 Hz supply frequency

5. Conclusions

This paper presented an experimental model built for studying the impact of modern variable speed drives on classical three-phase AC asynchronous motors, focusing on the assessment of the harmonic generation of this ensemble. For this purpose, a series of experimental measurements have been elaborated, concerning main power quality parameters such: specific active/ reactive/ apparent powers drawn from the power supply system, displacement and true PF, effective voltage/ current values and their total harmonic distortion level and also their spectrum at different operating frequencies (rated, below and above rated).

The experimental results are reported both on the power system supply part and also on the motor feeding part, at its terminals respectively, and confirm the presence of the harmonics in the sine wave sinusoidal forms of voltage and current. For operating frequencies below and above the rated 50 Hz frequency, the total harmonic distortion level increases even more rising up to 10 times the nominal operation frequency. These recorded harmonics are associated with a deformed operating mode and can considerably harm nearby sensitive equipment, causing various disturbance in their normal operation. At the same time, can cause downstream fed motors to overheat and increase in the noise produced, thus contributing to a lifespan decrease in time. [12] In this case corrective actions are strictly necessary, and in this purpose several filters must be taken into account, as active and/or passive filters and line choke inductances respectively. The passive filter assures the filtering of main harmonics (e.g. 5^{th} harmonic) and the active filter, determined by its accuracy and its dynamic, assures the filtering of the other harmonics. [13] [17] As well, as a key solution, another factor to be taken into consideration is the hybrid filters, as this alternative currently represents the best solution and most cost effective on the profile market. [14]

As a final conclusion, it can be mentioned that this elaborated experimental model is very useful within the research activity of variable speed drives and also in the industrial applications, representing a new approach and a scientific reference for concerned electrical project engineers and also for interested scientists in designing future active filters for low voltage applications.

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