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About some Effects of Voltage Distortion on End User's Equipment

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Abstract. The main objective of the paper is to assess the influence of supply voltage distortions, especially voltage harmonics on end user's equipment. Generally, harmonics are probably the most important issue of power quality, greatly influencing power flow.

In the introductory section, the main definitions of power quality and the main methods of harmonic analysis, namely Fourier series, Fourier transform and Wavelet transform.

The second section, devoted to experimental results, presents a series of measurements carried out for a setup composed of a programmable source supplying an induction motor, as end user equipment. The motor is supplied successively with three types of voltages, a clean sinusoidal voltage and two distorted ones, namely a 50% clipped voltage and a square voltage, synthesized according their harmonic content, and downloaded to a programmable supply source. The latest two waveforms are not arbitrarily chosen, being often encountered in practice, especially when the equipment is supplied through UPS's or power converters. The load torque of the motor was adjusted by a controlled electromagnetic powder brake.

Concluding, it can be said that distorted supply voltages, having an important harmonics content, highly affect the equipment operation, especially in terms of efficiency.

Key words

Voltage harmonics, current harmonics, Fourier analysis, waveform synthesis, energy efficiency.

1. Introduction

The term of power quality may be considered as an umbrella for a large variety of disturbances in electrical systems.

In recent decades, power quality has become a permanent concern for utilities suppliers, equipment manufacturers and, last but not least, for end users. Any problem manifested by variations in current, voltage or frequency that causes the malfunction of an equipment represents a power quality issue.

The specific literature abounds in power quality definitions [1-7].

The standard IEC/EN 61000-4-30 defines power quality as the characteristics of an electricity at a given point on an electrical system, evaluated against a set of reference technical parameters [8].

The Seventh Edition of the Authoritative Dictionary of IEEE Standards Terms, IEEE 100, published by Standards Information Network IEEE Press, defines power quality as the "concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment" [9].

This latest definition is at least vague if it is taken into consideration that actually equipment can be more or less sensitive, reacting more or less differently to power quality issues, generally depending on the severity of the problem.

However, starting from the term of "power quality" and because generically speaking, the electric power can be assimilated to the product between voltage and current, power quality should be a combination of voltage and current quality, so any deviation from ideal voltage and/or current, finally represents a power quality problem.

On the other hand, it is quite difficult to distinguish if the disturbances are voltage or current ones. Generally, it may be considered that a voltage disturbance originates in the power supply system, affecting equipment connected to the grid, whereas a current disturbance is generated by the equipment connected to the grid, impairing the quality of the electric power of the grid.

Unfortunately, this dichotomy does not resist to the simplest analysis, since switching an important load usually leads to an important current drawn from the grid, which in turn causes a temporary drop in the supply voltage (dip/sag). From the network's standpoint, the utility provider will feel it as a consumer problem, while any network-connected user will only feel a voltage variation and will consequently blame the utility provider for this issue.

An alternative definition of power quality can be the one distinguishing between power quality and continuity (reliability) of the power supply. Continuity includes interruptions, while quality is a term covering other perturbations. Short interruptions are in some cases considered to belong to continuity issues and in other cases is integrated in power quality issues.

Without entering intricate analysis, it may be recalled that both ideal voltage and ideal current have sinusoidal waveforms and at the same time constant amplitude and frequency. However, practical waveforms are far from being ideals, having in general different degrees of distortion.

A waveform distortion is defined as a permanent deviation from an ideal sinusoidal waveform, having the grid frequency and, in its signal spectrum the spectral components of these distortions.

Five types of waveform distortions are mainly present in practice:
- continuous component (DC offset)
- harmonic distortions
- inter-harmonics
- notching
- electromagnetic noise

Any device or non-linear load determines harmonic distortions. Passive non-linear consumers typically produce odd harmonics, while even harmonics appear to be produced mainly by active devices.

Deviation from the sinusoidal waveform determines the operation of alternating current equipment in a distorted regime. While some equipment (e.g. induction furnaces) are not disturbed by the presence of harmonics in the voltage waveform, in other cases (e.g. electric motors), the presence of voltage harmonics is harmful and consequently must be limited.

Harmonic components are sinusoidal signals of voltage or current having frequencies integer multiples of the power supply system frequency (50 and 60 Hz respectively). In addition to harmonic components, non-harmonic components may also appear in the grid: sub-harmonics or inter-harmonics produced by frequency converters or induction motors due to their slip.

Inter-harmonics are voltage or current disturbances having discrete frequencies (greater than the fundamental frequency), which are not integer multiples of the supply system frequency. Alternatively, so-called sub-harmonics, which are sinusoidal voltage or current components, whose frequencies are rational numbers smaller than the frequency of the supply system, may occur. Sometimes both inter-harmonics and sub-harmonics may present continuous broadband spectra. The main sources of these disturbances are the static frequency converters, cyclo-converters, induction furnaces and electric arcing devices.
Lately, there has been a better understanding of the origin and effects of inter-harmonics and sub-harmonics. They are generally the result of frequency conversion and are often variable versus the load. Inter-harmonic currents can excite quite severe resonances in the electric system if the inter-harmonic frequency becomes equal to the system's self-frequency.

Usually, harmonics are analyzed in time domain, in frequency domain or both in time-frequency domains [10 - 12]:
- In time domain, Fourier series are, in the most commonly used forms (the trigonometric and the complex-exponential series, the last one being more useful in applications due the simplicity of the calculations). Fourier series allow the representation of periodic signals.
- In frequency domain, in order to represent non-periodic signals, the Fourier transform is used. This transform makes possible to express a time domain function in frequency domain. However, the transform method suffers from limitations in handling discrete, discontinuous or multi-valued signals, quite common in nowadays electrical applications. Therefore, the Fourier transform was replaced by the discrete Fourier transform (DFT) and later by the fast Fourier transform (FFT). This latest architecture, using the fast Fourier transform, is recommended for the spectrum analyzers by the standard IEC 61000-4-7/2009.
- In both time and frequency domains, in the analysis of non-stationary signals, Wavelet transform is the only one useful.

2. Experimental results

The effects of voltage harmonics are studied for the experimental setup depicted in Fig. 2, consisting in an induction motor (a squirrel cage three phase induction motor of 0.46 kW, I_{max}=1.4 A, two pairs of poles, n_{sync}=1500 rot/min), a magnetic powder brake unit, a brake controller and a programmable source, namely CTS 15300iX from California Instruments [15].

Fig. 2 Experimental setup.

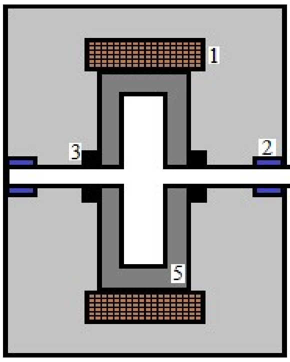

Fig. 3 A schematics cross section in a typical magnetic powder brake

The combination of the magnetic powder brake unit and the brake controller is used to measure the characteristics of the motor under test for different torques.

The principle of magnetic powder brakes is quite simple. Fig. 3 represents a cross section in a simplified model of such a braking system.
One may distinguish the main parts:
-1 a pair of coils
-2 bearings
-3 magnetic seals
-4 disc solidary bound with the output shaft
-5 gap filled with magnetic powder

The gap is filled with a fine magnetic powder, free flowing inside. An excitation current passing through the coils generates a magnetic field making the powder particles to align along the magnetic field lines, linking the output disk to the body of the brake. The braking torque is almost proportional with the magnetic field and consequently with the dc excitation current, except a slight unavoidable hysteresis.

Fig. 4 presents the block diagram of the braking system used in the experiments as load.

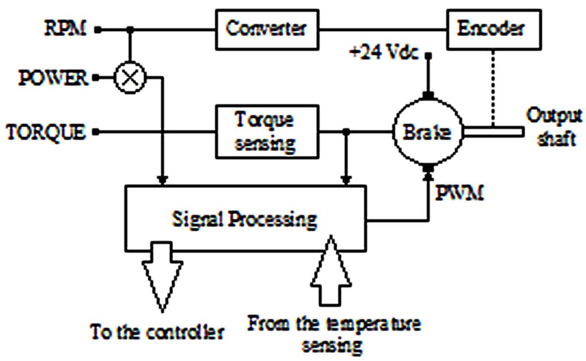

Fig. 4 The block diagram of the magnetic powder brake.

The braking system controller permits to set continuous values of the torque at the shaft of the induction motor, by the variation of the magnetic powder brake.

The programmable source used for testing is an instrument providing an efficient test solution, aiming to verify the product compliance with a large number of testing standards in AC and DC. Available for power levels ranging from 1250 VA to 30,000 VA, CTS Systems cover the complete range of single and three phase products that need testing to conform to existing and pending IEC standards.

The programmable source is controlled by the CIGUI firmware that can be used to control all aspects of the AC power source, allowing a full PC control without the need to use the front panel of the instrument.

The experimental setup was supplied successively by different synthesized waveforms of voltage, downloaded in the programmable power source.
A comparison will be performed, in terms of energy efficiency between three supply voltage waveforms.

It must be noted that the experiments don’t focus on the behavior of the induction motor for different loads which is the same in all cases, but for different distorted supply voltages.

Figs. from 5 to 7 depict the synthesized waveforms of the pure sine, the 50% clipped and the square supply voltages along with the corresponding currents drawn in no load conditions. These latest two waveforms are not simple hypothetical situations; they are often encountered in practice, especially when the equipment is supplied through several types of UPS’s.

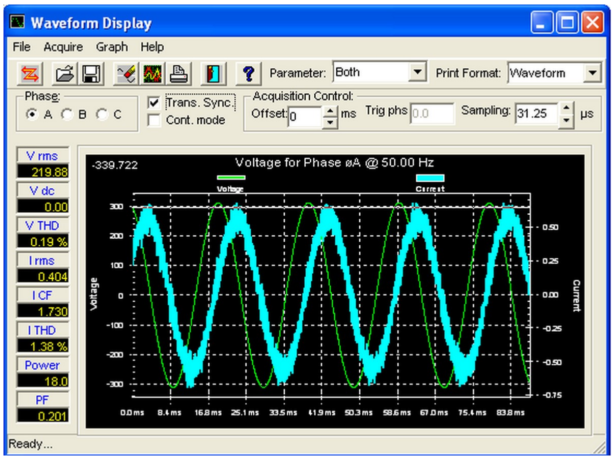

Fig. 5 The synthesized sine supply voltage and the corresponding current drawn in no load conditions.

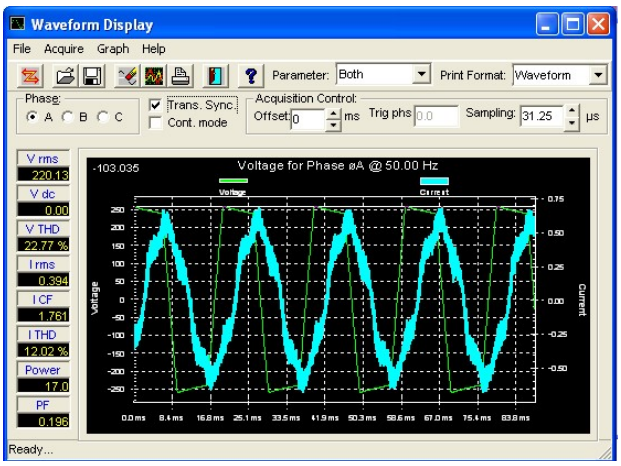

Fig.6 The synthesized 50% clipped supply voltage and the corresponding drawn current in no load conditions.

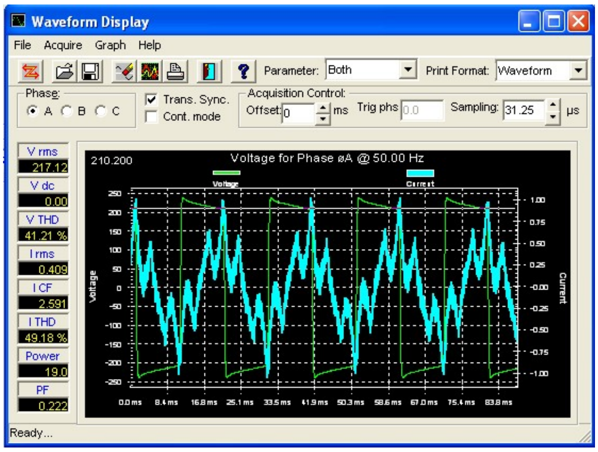

Fig. 7 The synthesized square supply voltage and the corresponding drawn current in no load conditions.

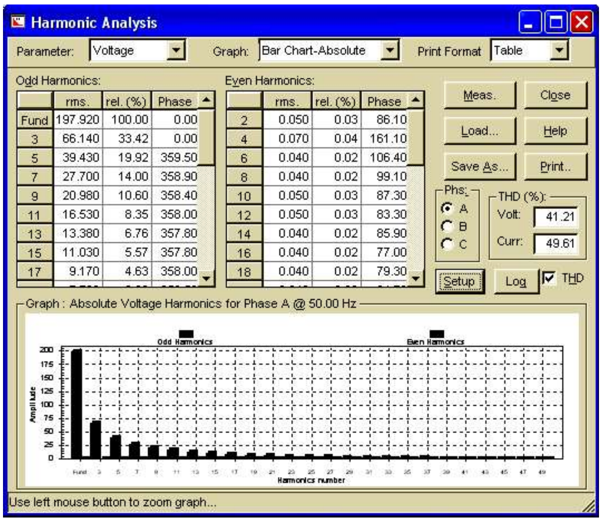

Fig. 8 The harmonic chart of the square supply voltage

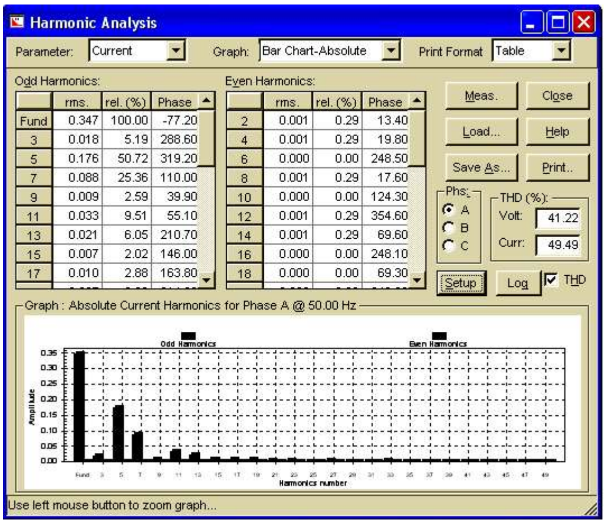

Fig. 9 The harmonic chart of the current drawn with square supply voltage

Figs. 8 and 9 present the harmonic content of the square supply voltage, having a THDV = 41% and a THDI = 49.5%. The harmonic chart of the amplitude of the voltage harmonics versus frequency has a decreasing shape, seemingly a hyperbolic one, while the harmonic chart of the current drawn from the system is quite irregular, being dominated by the fifth and seventh order harmonics.

It is well known that harmonic components can significantly impact motors, especially through voltage distortion, directly related with harmonic fluxes within the motor. Harmonic fluxes do not contribute to motor torque, rotating at a different frequency than the rotor and inducing high-frequency currents in the rotor. The main effect of voltage distortion is the motors' overheating, in case of a voltage distortion (THDV) exceeding the limit of 8% imposed by the standard EN 61000-4-7.

The fifth order harmonic which is a negative sequence one and the seventh order harmonic which is a positive order one, are dominant in the current harmonic chart and determine torsional oscillation, having as a resulting effect a magnetic field revolving at a speed of six times the speed of the motor shaft. Moreover, if the frequency of the torsional oscillations matches the natural frequency of the motor, severe damages may occur [16].

The main parameters are presented in Table I. One can see that in no load conditions, besides the total harmonic distortions of the voltage and current, the other parameters are quite close to each other. An exception is the crest factor in the case of the square supply voltage, which is with almost 50% higher compared to crest factor in the case of the pure sinusoidal supply.

It is obvious that the more distorted the supply voltage is the more distorted the waveform of the instantaneous power will be, along with a more important harmonic content.

Table I Main parameters of the different supplies

	SINE VOLTAGE	CLIPPED VOLTAGE	SQUARE VOLTAGE
THD_V	0.19%	22.77%	41.21%
I_{rms}	0.404 A	0.394 A	0.409 A
I_{CF}	1.730 A	1.761 A	2.591 A
THD_I	1.38%	12.02%	49.18%
Active power	18 W	17 W	19 W
PF	0.201	0.196	0.222

Figs. from 10 to 12 present the measured instantaneous powers in the three cases in no load conditions. In Fig. 12 the voltage distortion of the power is strongly visible.

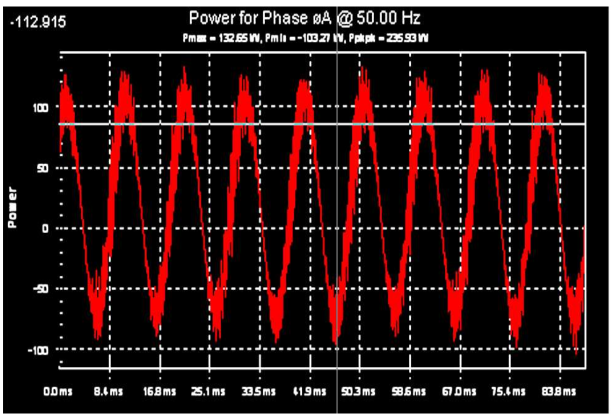

Fig. 10 The instantaneous power in the sinusoidal case

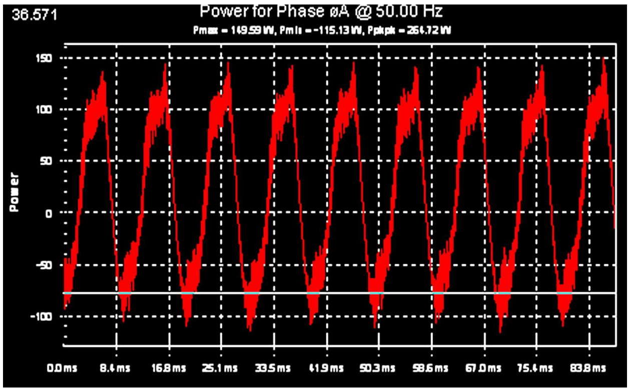

Fig. 11 The instantaneous power in the clipped case

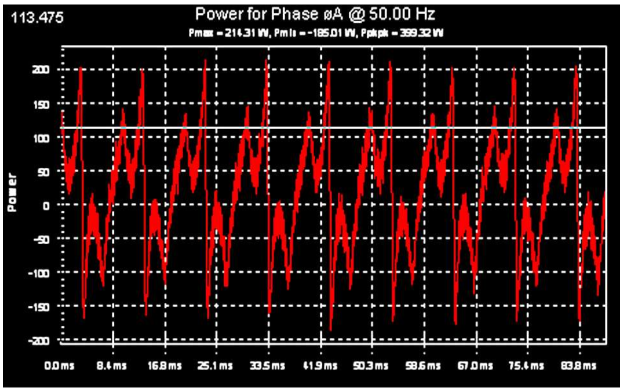

Fig. 12 The instantaneous power in the square case

Table II and Fig. 13 presents the active powers drawn from the source in the three situations. For the measurements performed at the same torque and a 50% load, the active power in the clipped case is exceeding with 18.8% the power drawn in the sinusoidal situation, and in the square case with 43%.

Table II Active power [kW]

	TORQUE (kg·m)	SINUSOIDAL VOLTAGE	CLIPPED VOLTAGE	SQUARE VOLTAGE
1	0	0.018	0.018	0.018
2	0.02	0.027	0.026	0.028
3	0.08	0.046	0.058	0.06
4	0.14	0.077	0.09	0.094
5	0.2	0.11	0.133	0.13
6	0.26	0.152	0.165	0.176
7	0.32	0.191	0.127	0.248
8	0.38	0.244	0.290	0.349

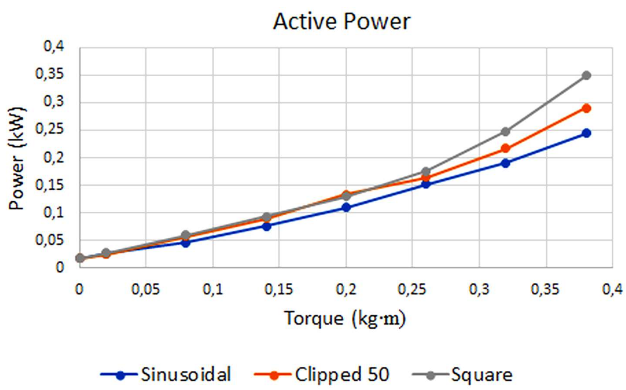

Fig. 13 The active power in the three cases

The load of 0.38 kg·m represents the maximum load that permits the operation of the motor supplied with square voltage. For a higher torque the operation of the motor became unstable.

For a torque of 0.14 kg·m, which permits the operation of the motor at a quite normal speed, the active power drawn from the supply source in the clipped case is exceeding with 22% the active power drawn in the sinusoidal situation, and with almost the same value of 22% in the square case.

Table III and Fig. 14 presents the apparent powers in the three studied situations. The apparent power contains the reactive power and the nonactive (fictitious) power. Thus, for the same torque at the motor's shaft, namely at a maximum load, the apparent power drawn from the supply grid in the clipped case is 39.3% higher than in the sinusoidal situation, and in the square case is 64.7% higher than in the sinusoidal situation.

Table III Apparent power in kVA

	TORQUE (kg·m)	SINUSOIDAL VOLTAGE	CLIPPED VOLTAGE	SQUARE VOLTAGE
1	0.01	0.102	0.092	0.094
2	0.02	0.105	0.094	0.097
3	0.08	0.107	0.110	0.112
4	0.14	0.119	0.130	0.139
5	0.2	0.135	0.166	0.171
6	0.26	0.152	0.197	0.217
7	0.32	0.189	0.251	0.310
8	0.38	0.244	0.340	0.402

For a torque of 0.14 kg·m, the apparent power drawn from the supply grid in the clipped case is exceeding with 9.2% the sinusoidal situation, and with almost the same value of 9.9% the sinusoidal situation. Again, the result reveals that both the clipped and the square voltage are almost equally harmful in terms of apparent power efficiency as well.

Finally, in Table IV and Fig. 15 are depicted the mechanical characteristics in the three situations studied.

The starting point is the same for all the three cases, but the situation is getting worse when the load increases. In maximum load, namely for a torque of 0.38 kg·m, the speed decreases with 17% in the sinusoidal case, with 24.7% in the clipped case and with 34.8% in the square case.

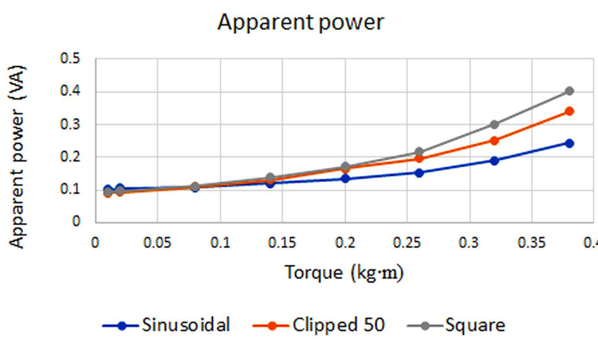

Fig. 14 The apparent power in the three cases

Table IV Mechanical characteristics

	TORQUE (kg·m)	SINUSOIDAL VOLTAGE (rot/min)	CLIPPED VOLTAGE (rot/min)	SQUARE VOLTAGE (rot/min)
1	0	1496	1496	1495
2	0.02	1488	1488	1484
3	0.08	1473	1457	1451
4	0.14	1445	1426	1408
5	0.2	1412	1384	1356
6	0.26	1370	1336	1282
7	0.32	1316	1240	1120
8	0.38	1240	1130	978

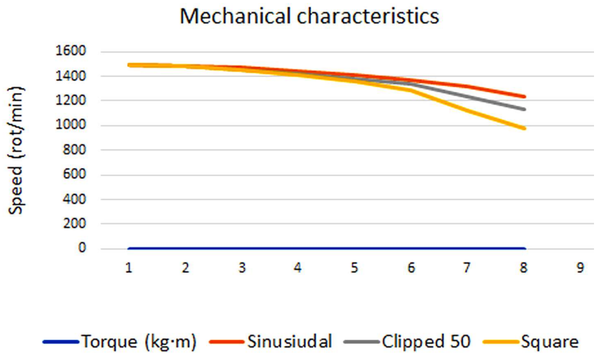

Fig. 15 Mechanical characteristics in the three cases

The slips in full load in the three cases are: $s_{\sin} = 17\%$; $s_{clip} = 24.6\%$; $s_{squ} = 35\%$. These slips are not suitable in practical applications. Efficient practical slips must be around 4-5%, corresponding in the present situation to a torque of (0.14-0.2) kg·m. As one can observe, for a torque of 0.14 kg·m, the corresponding slips are: $s_{\sin} = 3.7\%$; $s_{clip} = 4.9\%$; $s_{squ} = 6.1\%$.

The decrease of the efficiency of the active and apparent power, corroborated with the decrease of the slip in 50% load, represent a picture of the harmful effects of voltage harmonics on end user's equipment.

3. Conclusions

In short, from the previous section, it is clear that voltage harmonics determine harmful effects in end user's equipment with respect of efficient operation.

However, only the presence of voltage harmonics themselves, permit until a certain extent of the shaft torque a quite decent operation of the induction motor. But, it was visible that voltage harmonics determine in turn distorted currents, rich in harmonics, which in the case of induction motors determine several side issues (e.g. overheating and shaft oscillations).

At the same time, from the characteristics presented in the previous section, especially the power versus torque characteristics and the mechanical speed versus torque characteristics, it is obvious that the efficiency is severely reduced if voltage distortion and harmonic content of the voltage and of the current increase.

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