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Influence of constructive parameters and power signals on sound quality and airborne noise radiated by inverter-fed induction motors

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ABSTRACT

This work presents the result of a study of the acoustic quality of noise emitted by a three-phase, induction motor fed with various modulation techniques (Pulse Width Modulation, PWM). It complements the classical study of noise emitted by rotating electrical machines, based on acoustic emission levels. For this, the psychoacoustic parameters of Specific and Total Loudness, as well as Total Roughness were used. These were applied to the noise emitted by a 4-speed, Dahlander-type motor to identify their contribution to the acoustic quality of distinct pole-number configurations as well as the different control-parameter values of each of the studied techniques. The modulation techniques employed have been analyzed in previous research in which was determined their contribution to the noise levels emitted by a machine of similar characteristics as that employed here. Results are checked experimentally and compared to the sound-pressure level; showing the noise emitted and the sound quality do not coincide for a given combination of parameters. Moreover, the choice of the best modulation strategy changes depending on if the aim to achieve is less harmonic distortion (HIPWM-FMTC), less heating of associated electronics (SLPWM) or a lower acoustic emission level (HIPWM-FMTC2). Finally, with the present study an attempt is made to compliment and corroborate the results obtained up until now, as well as initiate a new focus of analysis that can serve as the basis for future research of other operation forms and regimes, and also other kinds of rotating electrical machines.

1. Introduction

Of the three components of noise that exist in electrical motor's normal operation, the most relevant are aerodynamic and electromagnetic. Although the latter is the one that is most noticeable at low speeds of operation, it is the aerodynamic component that gains prominence when the speed of the machine is increased.

Many of the control techniques of electrical machines are based on what is known as Pulse Width Modulation or PWM techniques. These types of techniques pursue different outcomes by acting on the signal that feeds each type of machine, for example: improved performance, increased control, decreased consumption, or improved quality of the power signal itself. Some of these techniques have been recently developed and they have been tested

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Nomenclature

f	supply frequency, 50 Hz	K_c	modulation constant for HIPWM-FMTC technique
f	frequency of the fundamental of modulated signal	k_f	modulation constant for HIPWM-FMTC technique
f_c	carrier signal's central frequency for HIPWM-FMTC technique	L	loudness (Sone)
f_F	frequency of the triangular carrier signal for HIPWM-FMTC2 technique	M	number of pulses per period
MMF	magneto motive force	m_f	modulating signal's frequency
HIPWM-FMTC	Harmonics Injection Pulse Width Modulation with Frequency Modulated and Triangular Carrier	R	roughness (Asper)
		s_1	number of stator slots
		s_2	number of rotor bars
HIPWM-FMTC2	Harmonics Injection Pulse Width Modulation with Frequency Modulated and Triangular Carrier 2	SLPWM	Slope Pulse Width Modulation
		SPL	sound pressure level (dBA)
		THD	total harmonics distortion
k	real number for slope PWM (SLPWM) technique	α	control parameter for the effective slope for HIPWM-FMTC2 technique
		μ	slope of trapezoidal modulator wave for slope PWM (SLPWM) technique

with the objective of reducing acoustic noise level [1–8]. On the other hand, certain constructive parameters of the machine such as pole number also condition the level of noise that it generates [9–13]. These do so; not only in terms of speed, but the distribution of windings in slots, input current waveform distortion, air gap permeance fluctuations, rotor eccentricity, and phase unbalance give rise to mechanical deformations, vibrations and changing electromagnetic acoustical noise [14]. In this sense, the results achieved in these researches should be applied to other similar motors whether these conditions are keeping, although acoustical noise could change depending on both the power and charge of the motor. Also there are determining factors at the time of selecting a specific technique or control parameter for the distribution of magnetic field harmonics in the machine's air gap [15–20].

Commonly, the study of electrical motors' acoustic behavior is focused on determining noise levels either in general terms or as a set of frequency bands within the audible range. In this way, it is understood that electrical machines, or better said specific operating modes of these machines that generate greater noise levels, are "worse" than others with a lower acoustic emission level, see Fig. 1. Traditionally, the sound pressure level A-weighted decibels (dBA) have been employed for this type of comparison; however, a more developed concept of acoustics has now emerged that seeks not only to minimize emitted sound but also to fundamentally improve it. It is based on a perception of sound that simulates the operation of the human ear. This concept is called psychoacoustics and it is used in a multitude of processes from appliances to vehicles in order to improve the quality of the sound that is emitted [13,21,22]. Additionally, comparison is done through jury testing where people evaluate emitted sound with developed metrics of sound quality based on sound parameters and perception and known as Loudness, Roughness or Sharpness, among others [23].

There are numerous studies focused exclusively on the noise level that certain electrical machines generate when they are fed by different modulation techniques [4,11,24,25]. Nonetheless, up until now there is no known research based on criteria different from the greater or lesser sound emission level of these machines, as with those related to the acoustic quality of emitted sound. In this work, a methodology of study is presented whose objective is to determine the best combination of a machine's power-signal, control variables, which will translate into an optimal acoustic emission, not only in terms of noise level but above all in terms of sound quality. Fig. 1 shows an overview of the main elements and parameters studied in this work.

2. Materials and methods

2.1. Parameters of sound quality

Parameters of sound quality refer to those whose values reflect the pleasantness or unpleasantness that a particular sound might achieve, and whose study constitutes what is known as "psychoacoustics".

Methods have been developed that enable the evaluation of some properties of a sound through descriptors such as "Loudness", "Roughness", "Sharpness" or "Fluctuation Strength", among others. Only obtaining Loudness is standardized. With regard to the characterization of sound quality, there are no metrics defined for every sound [26,27].

For example, for an internal combustion engine, some authors employ only Loudness parameter [28], while others also use Roughness and Sharpness [29,30]. In the case of electrical machines, there are no previous studies on sound quality. Thus, for its characterization Loudness and in critical cases also Roughness are employed to observe if there is a just-noticeable difference between emitted sounds. These parameters are briefly defined below.

2.1.1. Loudness

The parameter of Loudness is a subjective measure of the intensity with which sound is perceived by the human ear. This metric determines how strong one sound is in relation to another. Its unit is the "Sone".