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CHARACTERIZATION OF HARMONIC DISTORTION ON THE ELECTRIC NETWORK CAUSED BY A BATTERY CHARGER FOR ELECTRIC VEHICLES

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ABSTRACT

The development of new technology on electric vehicles (EV) is intended to counter the damage in the environment, which is a current issue for society. All electric vehicles need a recharging system to store energy whether is from a renewable power source or from an electric power distribution. Most of these systems are connected to the electric network which causes bad quality during the energy supply. In this paper it is shown the effects of a battery charger for EV when connected to the electric network, on the analysis there is an experimental insight and a simulation. In the experimental part, a Schumacher SE-4225 battery charger is presented and its mathematical model evaluated, it takes place the recharging of two types of Lead-acid batteries (a liquid electrolyte/Everstart EXTREME battery and a gel/TROJAN VRLA SG-70 batteries), with a power quality analyzer the harmonic distortion is measured. The simulation part is developed, based on an equivalent circuit's model of a battery charger, using a MATLAB/Simulink, also presenting the characteristics and electric parameters of each component. They are both processes are analyzed and compared.

Keywords: Electric Vehicle, Battery Charger, Power Quality, Harmonics, Analysis

INTRODUCTION

The electric car represents itself an improvement on the efficiency of energetics, less dependence on oil consuming for the car industry, and the reduction of air pollution. An electric car is an automobile totally or partially propelled by electrical energy stored in batteries which are charged by power systems connected to the electric network or renewable source.

For many years the use of batteries has had a great impact on many different devices and on electric vehicles, nowadays more complex systems have been developed which requires a major

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power supply. There is a necessity of more capable battery chargers to supply the power required for these kinds of batteries (Perujo and Ciuffo, 2009).

A battery charger is a nonlinear device used to put energy or voltage into a battery or batteries. The existence of devices based on nonlinear load, installed in the electric system, has increased the presence of harmonic distortion in the current and in the voltage, which originates many problems on the power quality (Dugan and Macgrhanagan, 2004).

In recent years there have been many attempts to reduce harmonic distortion in electric systems to improve the power quality. The area of harmonic's analysis has experienced many significant advances and has developed more accurate model devices, simulation methods, and analysis procedures for a better understanding of harmonics (Wang *et al*., 2001). However, the expected growth of electric vehicles (Perujo and Ciuffo, 2009; Sainz *et al.*, 2011), and procedures that require battery chargers may result in serious problems in the power quality of existent networks, primarily where the demand is greater. That is the reason why this study on battery charger behavior is conducted as experimental, its equivalent circuit is analyzed and a model of its functioning is developed, which is taken as reference for developing a simulation of its behavior.

Systems that affect the power quality

The term power quality applies to a vast extension of electromagnetic phenomena and voltage variations caused by disturbances in an electric system. The IEC (International Electrotechnical Commission) classifies the electromagnetic phenomena in conducted low-frequency phenomena (harmonics, interharmonics and others), radiated low-frequency phenomena, conducted high-frequency phenomena, radiated high frequency phenomena, Electrostatic discharge phenomena and Nuclear electromagnetic pulse (Dugan and Macgrhanagan, 2004).

One of the most common problems that affect power quality on low voltage electric systems is the distortion of the wave as a result of the "harmonic distortion". This phenomenon it is important due to the increase of electric devices usage on many processes, which work with a nonlinear load.

There are many nonlinear loads that affect the electrical distribution network in different ways, this type of loads can produce transients, overcharging, voltage lows, interruptions and primarily harmonic distortion. The amount of problems that a nonlinear load can generate depends on the voltage or current magnitude that it is demanded.

Previous harmonic propagations were related to the design and the management of power transformers and rotating machines. In fact, the first power source of harmonics was the magnetic current of power transformers (Guzman *et al.*, 2008).

The power transformers and rotating machines, in stable state, do not create a significant distortion in the electric current, when operated out of their specifications, they can rise their harmonic content with considerable levels of distortion. Other loads that produce harmonics are the electric arc furnaces, switched-mode power supplies, electrical ballasts, and electric vehicles battery chargers (Tremblay *et al.*, 2007).

Modelling of the battery charger

In order to achieve the characterization of the battery charger's effects, it was necessary to delimit the properties of the charger and the batteries. On the experiment it was used a Schumacher SE-4225 battery charger, with four charging stages, as well as two Lead-acid batteries, a liquid electrolyte battery (Everstart EXTREME) and a gel electrolyte battery (TROJAN VRLA SG-70).

The battery charger behaved as a monophasic full wave rectifier which has four stages of charge, as a result it gives four distinct current values to the output. Therefore, to be able to make the analysis, only one of the four stages was represented by the electric network equivalent to a battery charger in just one phase (Figure 1).

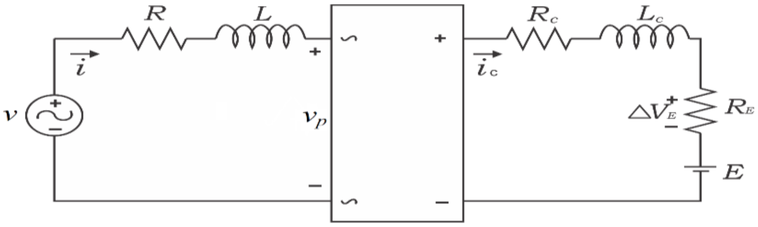


Figure 1: Equivalent circuit of EV battery chargers

The network consists on a one phase diodes bonded with an inductor L and a resistance R that represents the equivalent network of the transformer. The resistance R_c and the inductance L_c constitute the impedance that stimulates the E charge the electromotive force (emf) of the battery when charging, along with its associated resistance R_E. v represents the supply voltage, $v(\theta) = \sqrt{2}\sum_{k=1}^{\infty} v_k \cos(k\theta + \theta_{vk})$ and θ_{vk} is the *v* out of phase. The battery charger network may work in a continuous mode or discontinued mode (Sainz *et al.*, 2011), being the latter the most common modelling for this type of network.

For a part of *v* defined as E/v_1 $(0.759 < E/v_1 < 1.4142)$, the first joint by zero of the current i [A point (Figure 2)] occurs before it joints by natural voltage zero v_p when the inductances are minor. On the other hand, when the supplied voltage is lesser than emf E, the next joint by currents zero occurs i and there is no flow among diodes (the diodes that are on go out). They remained out until the rectified voltage supplied is superior to emf E [B point (Figure 2)]. In this conduction mode it can be stated that:

a) The current *i* equals zero as a result of the out diodes. [I and III segments (Figure 2)]
b) The current *i* flows through a pair of diodes to charge the battery [II and IV segments (Figure2)].

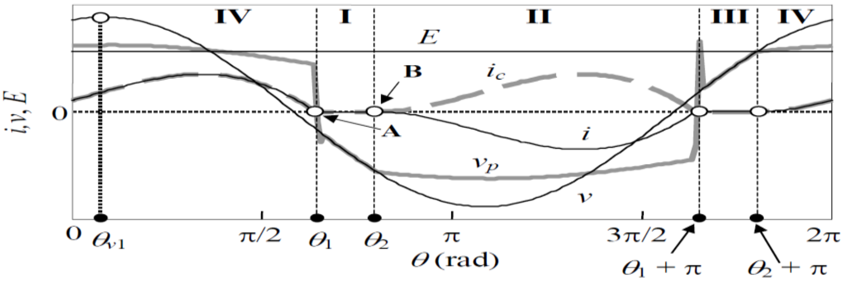


Figure 2: Discontinuous conduction mode of EV battery charger equivalent circuit

According to Figure 2 the switching of the angles θ_1 andθ_2, define the behavior of the charger, taking into account the conditions of half wave symmetry. The current´s wave forms are analyzed when diodes do not conduct, segment I $(\Theta_1 < \Theta < \Theta_2)$ and when conduct, segment II $(\Theta_2 < \Theta < \Theta_{1+\pi})$. When diodes do not conduct the current on the network equals zero (1).

$$i = 0,\ i_c = 0 \tag{1}$$

When a pair of diodes conducts, the current $i_c = -i$, according to the wave nature of the segment II on Figure 2. As a result, an equivalent network can be recognized (Figure 3). Then it can be said that $R_T = R + R_C + R_E$ and $X = (L + L_C)\omega$ becomes to the equivalent network (Figure 4).

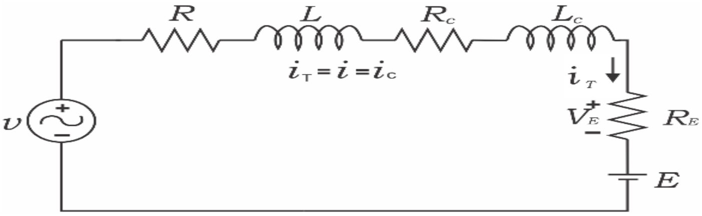


Figure 3: Equivalent circuit when the diodes conduct

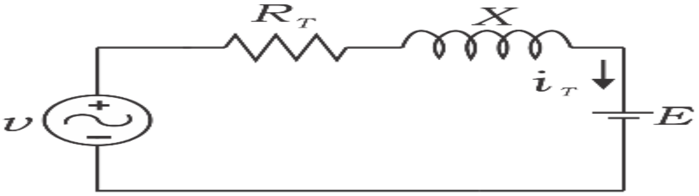


Figure 4: Final equivalent circuit when the diodes conduct

By applying Kirchhoff's voltage laws it is possible to obtain (2)

$$R_T i + X\frac{di}{dt} - E = v,\ i_c = -i \tag{2}$$

When solved (2) it is obtained *i* (3).

$$i = -i_c = ke^{-\frac{R_T}{X}\Theta} + g(\Theta) + \frac{E}{R_T} \tag{3}$$

Where

$$g(\Theta) = \sqrt{2}\sum_{k=1}^{3,5,\dots} I_k \cos(k\Theta + \vartheta_k),$$

$$I(k) = \frac{v_k}{\sqrt{R_T + (kX)^2}},\ \Theta = -tg^{-1}\left(\frac{kX}{R_T}\right) \tag{4}$$

The expression of constant *K* of (3) it is obtained from the continuity condition, (5).

$$K = -e^{\frac{R_T}{x}\Theta_2}\left(\frac{E}{R_T} + g(\Theta_2)\right) \tag{5}$$

The current in each stage of the charger depends on the values of inductance and resistance associated to every input of the transformer. Taking as a reference the equivalent network of Figure 1, the equivalent network of the battery charger used is established (Figure 5).

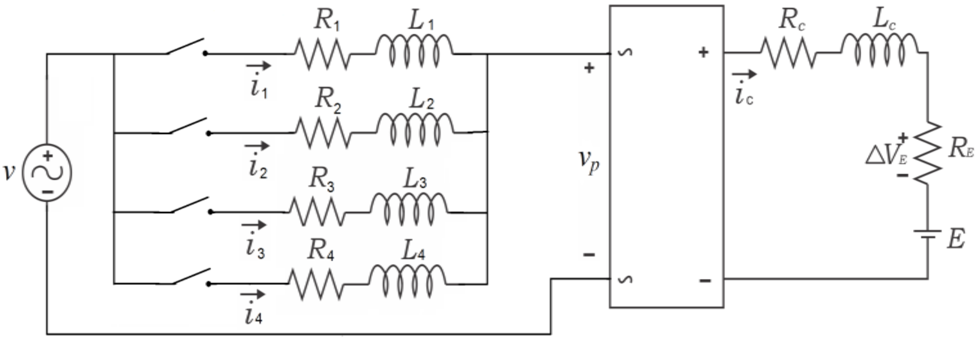


Figure 5: Equivalent circuit of Schumacher SE-4225 battery charger

According to Figure 5 network, the current values can be determined in every stage of the charge (6), (7), (8), (9).

$$i_1 = K_1 e^{-\frac{R_{T1}}{X_1}\Theta} + g(\Theta) + \frac{E}{R_{T1}} \tag{6}$$

$$i_2 = K_2 e^{-\frac{R_{T2}}{X_2}\Theta} + g(\Theta) + \frac{E}{R_{T2}} \tag{7}$$

$$i_3 = K_3 e^{-\frac{R_{T3}}{X_3}\Theta} + g(\Theta) + \frac{E}{R_{T3}} \tag{8}$$

$$i_4 = K_4 e^{-\frac{R_{T4}}{X_4}\Theta} + g(\Theta) + \frac{E}{R_{T4}} \tag{9}$$

Simulation and experimental development

The charging took place for the Lead-acid battery with liquid electrolyte and gel electrolyte making a simulation in MATLAB\Simulink. The simulation was based on the equivalent network of the battery charger (Figure 5), adding the Lead-acid battery and the transformer charger features, Table. 1, 2.

Table 1: Features of Lead acid batteries

Type of battery	Nominal voltage (V)	Capacity (Ah)
Lead-acid (liquid)	12	50
Lead-acid (gel)	12	75

Table 2: Features transformer

Charge rate	Transformer input	Transformer output	Charger output

		L_p (*mH*)	R_p	V_p (V_{rms})	L_s(*mH*)	R_s	V_s (Vrms)	V_o (V_{dc})
Slow	2A	21.2	1.06	84.4	480.2	0.13	10.96	11.28
Medium	20A	29.39	0.81	104.56	431.8	0.13	13.53	13.9
Fast	40A	38.24	0.68	119.9	432.5	0.13	15.45	15.86
Rapid	60A	57.68	0.62	140.02	430.7	0.13	17.96	18.57

The results obtained from the simulation show the effects that the battery charger causes on the current and on the voltage. The input voltage is completely sinusoidal and the current shows the distortion generated in every charging stage, slow 2A (Figure 6), medium 20A (Figure 7), fast 40A (Figure 8) and rapid 65A (Figure 9), on the Lead-acid battery with liquid electrolyte.

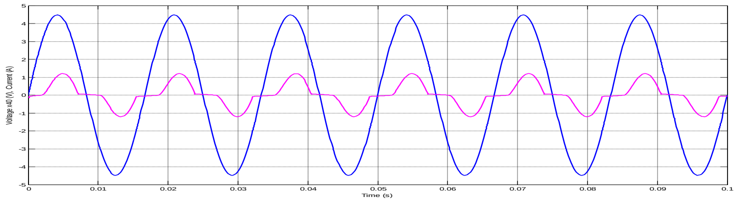


Figure 6: Simulated current and voltage waveforms (slow charge)

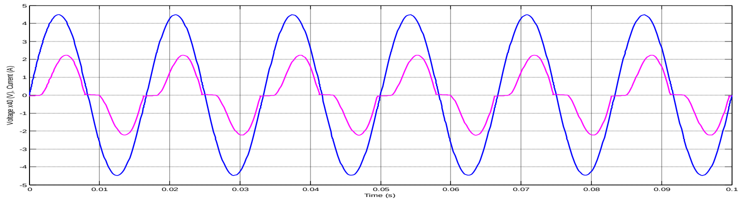


Figure 7: Simulated current and voltage waveforms (medium charge)

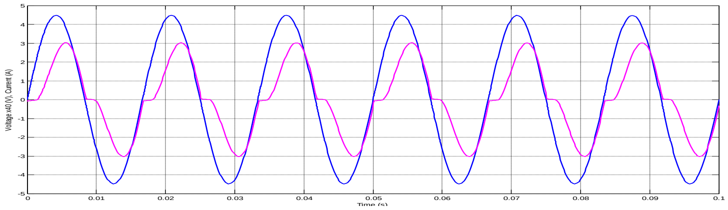


Figure 8: Simulated current and voltage waveforms (fast charge)

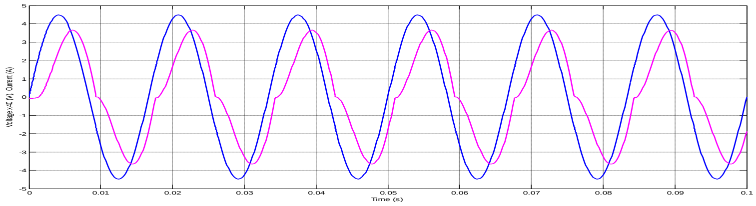
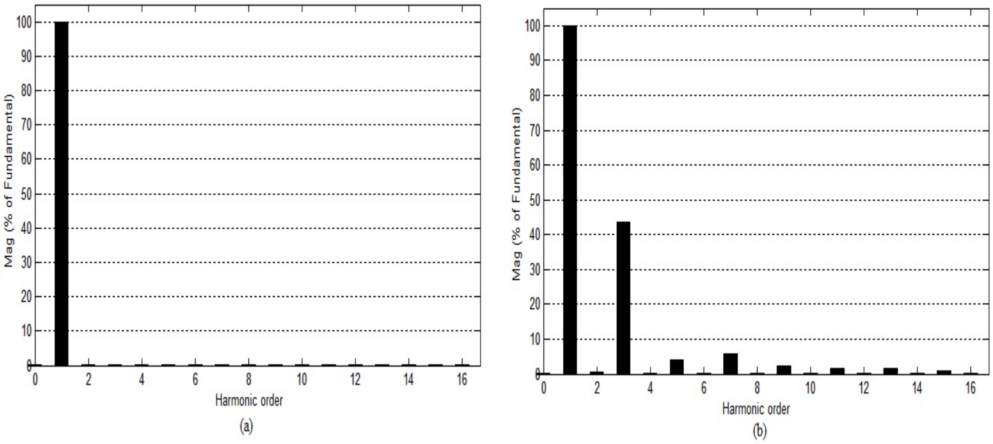


Figure 9: Simulated current and voltage waveforms (rapid charge)

On the simulation phase the distribution of harmonics was determined for both types of battery. On the next images the voltage and current harmonics are shown (Figure 10), for slow charging.



(a)

(b)

Figure 10: Voltage and current harmonics (simulation): (a) Voltage harmonics (b) Current harmonics

On the experimental phase, the charging of the Lead-acid battery with liquid electrolyte and gel electrolyte for every charging stage and with the help of the advanced energy FLUKE 43B analyzer, the voltage and current behavior was achieved when the battery had about 10% of its charge. On Figures 12, 13, 14, 15, it is presented the current and voltage of line for the liquid electrolyte Lead-acid battery.

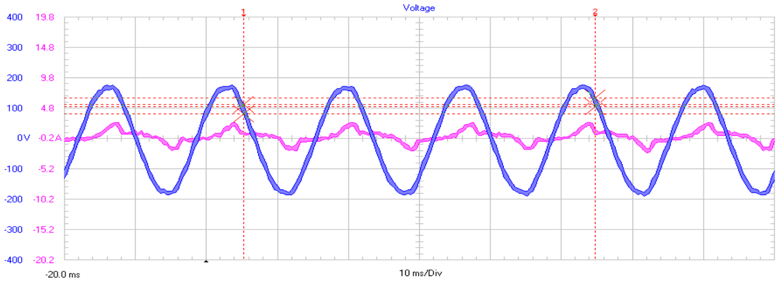


Figure 11: Measurement current and voltage waveforms (slow charge)

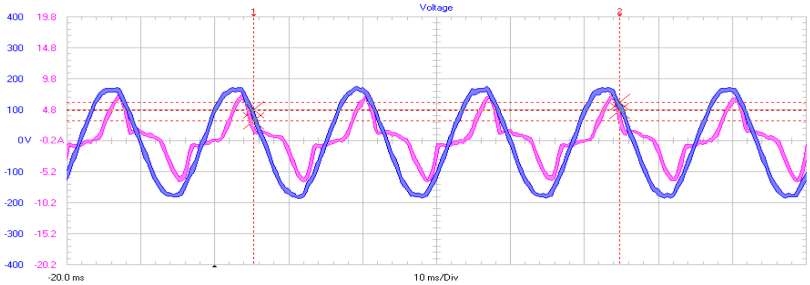


Figure 12: Measurement current and voltage waveforms (medium charge)

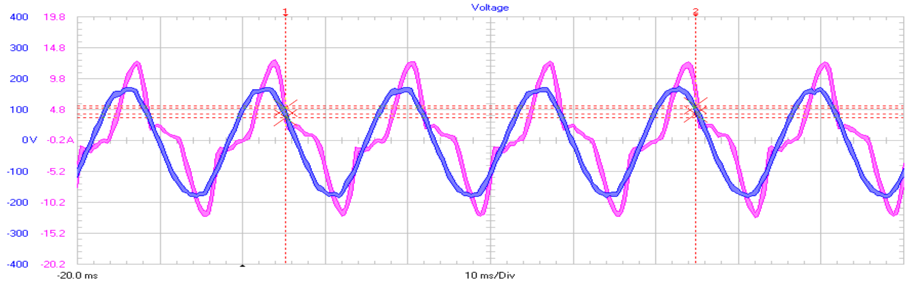


Figure 13: Measurement current and voltage waveforms (fast charge)

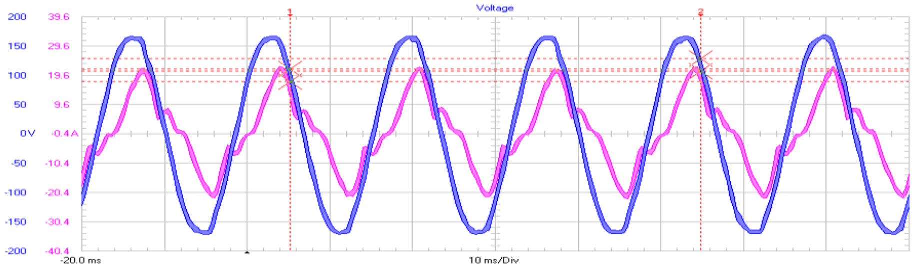
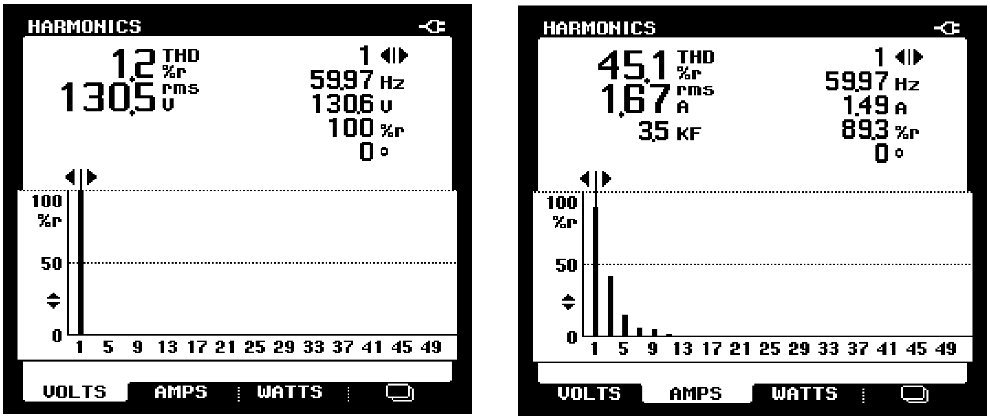


Figure 14: Measurement current and voltage waveforms (rapid charge)

According to the images, it is notorious that the current contains distortion and as the current speed increases the distortion decreases. On the other hand, the voltage preserves its form in every charging stage.

Through the FLUKE 43B analyzer the total harmonic distortion (THD) of the voltage and current of every type of charging stage was determined. Figure 15 shows the harmonics distribution for slow charge. The current holds enough harmonics to infest the electric network, due to the total harmonic distortion of currents (THDI) values on the slow charging stage.



(a) (b)

Figure 15: Voltage and current harmonics (measurement): (a) Voltage harmonics (b) Current harmonics

RESULTS

As a result of this work a comparison of the outcomes is made. On Table 3 and 4 the values of simulated and measured THDI and total harmonic distortion of voltage THDV for each stage of the process of battery charging can be appreciated.

Table 3: Battery charger harmonic distortion for Lead-acid battery (liquid)

Lead-acid (liquid)					
Charge rate		Measurement		Simulation	
		THDI (%)	THDV (%)	THDI (%)	THDV (%)
Low	2A	45.1	1.2	44.2	1.17
Medium	20A	39.1	1.3	36.7	1.22
Fast	40A	34	1.3	31.5	1.26
Speed	65A	23.5	1.5	21.8	1.4

Table 4: Battery charger harmonic distortion for Lead-acid battery (gel)

Lead-acid (gel)					
Charge rate		Measurement		Simulation	
		THDI (%)	THDV (%)	THDI (%)	THDV (%)
Low	2A	44.3	1.3	44.19	1.22
Medium	20A	38.3	1.2	36.26	1.16
Fast	40A	33.6	1.1	31.9	1.05
Speed	65A	22.5	1.1	20.17	1.07

The total harmonic distortion of the current decreases on the two batteries as the speed of the current rises during the charging process. It reaches values proximate to 50% in a state of minor charging, though, the current demanded on the charging is low.

On the two kind of Lead-acid batteries, the voltage of the total harmonic distortion increases in values lower than 2%, which does not implies any harmonics issues on the current network and it is under the standard of CFE L-000045 of the Federal Commission of Electricity in Mexico (CFE, 2011). In order to observe the voltage and the current total harmonic distortion behavior triggered by the battery charger, a comparative graphic was made for each distortion parameter (Figure 16, Figure 17).

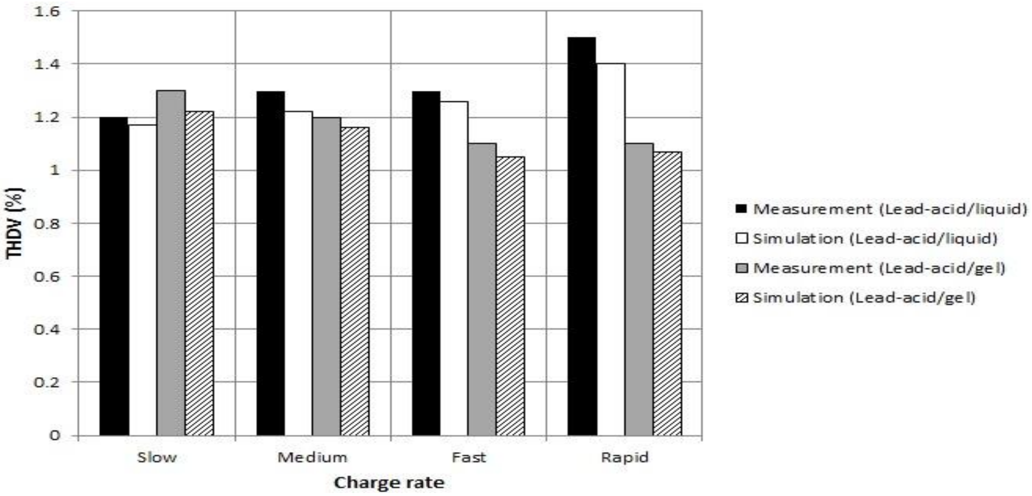


Figure 16: THDV of battery charger

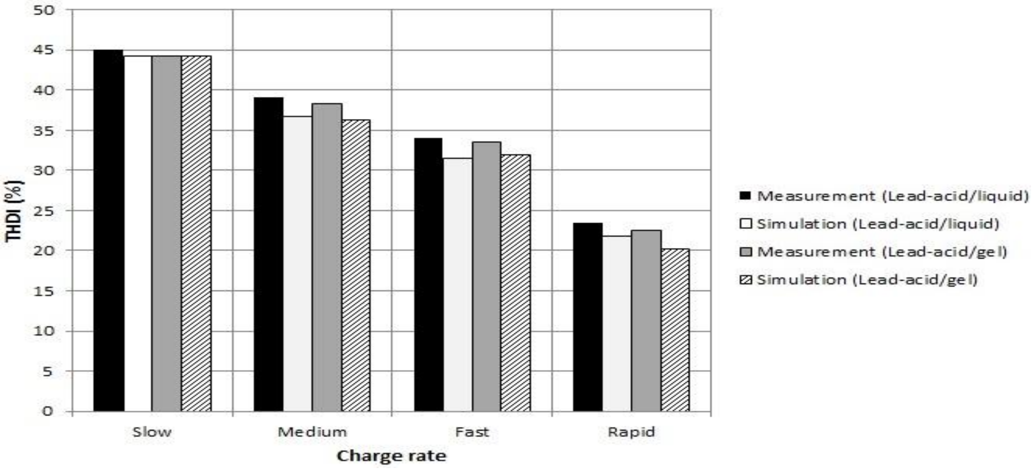


Figure 17: THDI of battery charger

In order to achieve a better perspective of the battery charger impact, measurements of THDV and THDI were taken from a different nonlinear load (electrical ballast). On Table 5 the values obtained from the measurement are represented (ISB Sola Basic 650-248).

Table 5: Electric ballast harmonic distortion

Type of load	TDHI (%)	TDHV (%)
Electric ballast	18.2	14

The THDI value is inferior to most values of the THDI battery charger. On Figure 18 and 19 the values obtained from the charging stage and the nonlinear charging graphics are exposed.

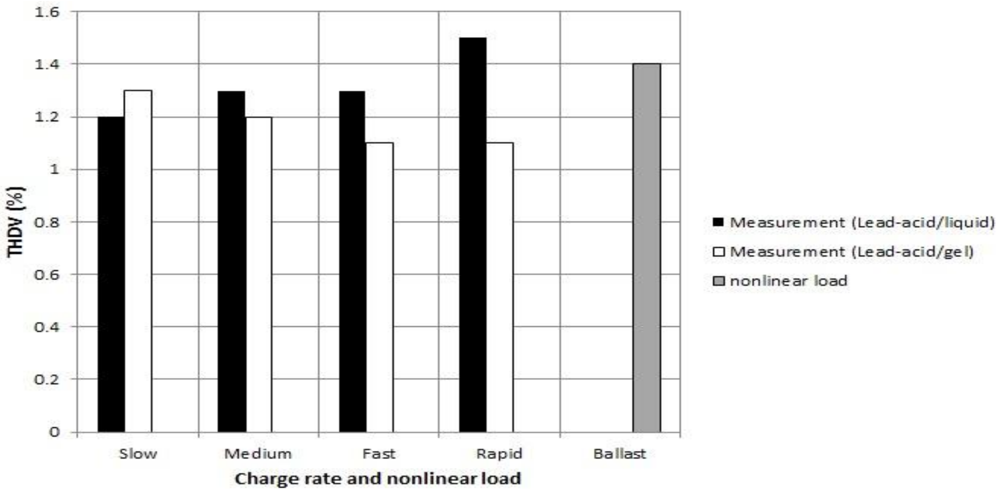


Figure 18: THDV of battery charger and nonlinear load

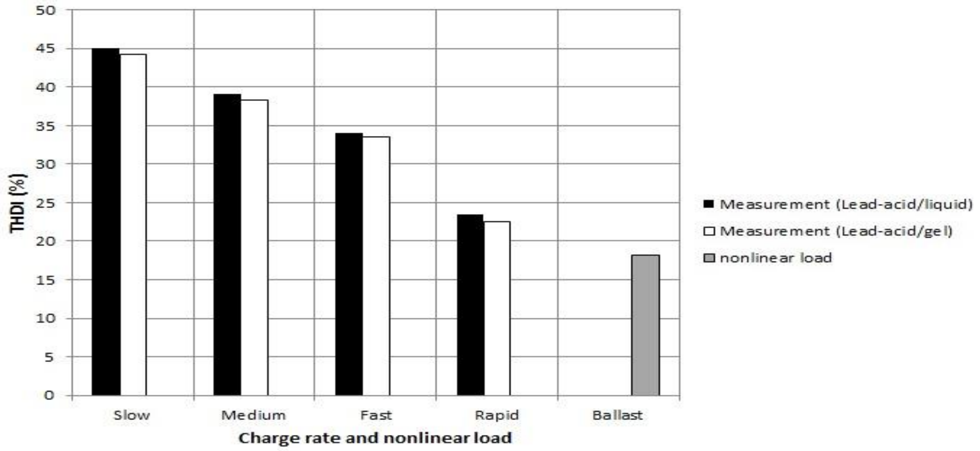


Figure 19: THDI of battery and nonlinear load

CONCLUSIONES

An experimental and a simulation study on the harmonic distortion of a battery charger was conducted. The study was focused on the effects generated by a regular charger, mainly used in battery’s charging for electric vehicles. It is been proved that one of the most relevant effects is the total harmonic distortion that occurs in the current. The THDV was also measured, and it was confirmed that the voltage preserves its wave form without any variation in spite of the charging speediness.

Subsequently, the distortion of an electrical ballast with nonlinear load commonly used on domestic networks was determined. The THDI values were close to 15%, however they are still inferior to the

THDI battery charger values. On the other hand, the THDV was measured, and it was corroborated that this type of nonlinear load does not affect voltage.

In the study conducted it was demonstrated that the battery charger presents issues in the electric network due to the distortion phenomenon generated. This paper allows to offer solutions and recommendations to avoid damages in other systems, simultaneously connected to the electric power supplier.

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