Experimental Measurements and Computer Simulations of Home Appliances loads for Harmonic Studies

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***Abstract*—Due to the advancement in power electronics industry, home appliances become more power electronics based. The widespread use of these nonlinear loads increases the harmonics in distribution systems and affects the voltage quality of power systems. In order to quantify the harmonics produced by LCD TV, regular refrigerator and Adjustable Speed Drive (ASD) washer precisely, accurate modeling of these loads are required. Firstly, experimental measurements have been carried out to quantify the harmonics injected by the loads. Then, Matlab Simulink is used to model and simulate these loads to give close results to the experimental measurements. Such models help engineers and researchers to evaluate the harmonics that exist within a residential sector.**

Keywords-LCD TV; regular refrigerator; ASD washer; harmonics; distortion; THD

I. INTRODUCTION

The increasing use of power electronics based nonlinear loads nowadays concerns engineers regarding the distortion levels and their impacts on the quality of power system networks. In general, nonlinear loads such as LCD TV, regular refrigerator and Adjustable Speed Drive (ASD) washer can cause severe problems to power systems and end users such as increased voltage distortion, power systems overloading, system losses, impact on energy metering, interference with communications networks, thermal effects on rotating machines, incorrect tripping of circuit breakers, a decrease in the overall system efficiency and worsening of the system reliability [1-6].

Rather than modeling the loads considered in this paper in detail, the Constant Load Power (CLP) model is used. The CLP model was first introduced in [7, 8] and has been proved to give very close results to the PC full model and experimental results. In order to validate that the CLP model can also be used to model LCD TV, regular refrigerator and ASD washer, simulation results of these nonlinear loads using the CLP models are compared with experimental measurements.

To prevent any variation within the systems from affecting the harmonics generated by the LCD TV and regular refrigerator, the loads were supplied using a programmable AC source Chroma^{TM} 61511 [15] that helps in isolating the test rig and filtering out harmonics and fluctuations from the main power supply. The conditions of the system under which the experiments conducted were 240V, 50Hz and 0.25Ω. The input voltage and current of the LCD TV, regular refrigerator and ASD washer were monitored using a KinetiQ PPA1530 Power Analyzer [9].

Voltage and Current Total Harmonic Distortion indices (THD_v and THD_i) as well as Individual Current Harmonic Distortion (IHD) up to the 11th order harmonic are considered in this paper. The Root-Mean-Square (RMS) values of the input voltage and current, Power Factor (PF), active (P), nonactive (N) and apparent power (S) are also taking into account. These quantities are calculated according to the IEEE Std 1459 [10].

The paper is organized as follows: section II discusses the harmonics and power indices calculations according to the IEEE 1459-2010. Section III presents the CLP model that used to simulate the LCD TV, regular refrigerator and ASD washer. Then, experimental and simulation results are introduced in section IV. Finally, Section V presents the summary and conclusions.

II. HARMONIC INDICIES CALCULATIONS ACCORDING TO IEEE 1459-2010

The presence of harmonics makes the voltage and current power system waveforms to be nonsinusoidals. The calculations of power system quantities such as voltage and current RMS values, power factor, active and apparent power needs to consider the presence of these harmonics. IEEE 1459-2010 defines in detail how these quantities can be calculated taking into consideration harmonics as shown in the following equations [11].

The RMS voltage and current are:

$$V_H^2 = V^2 - V_1^2 \quad (1)$$

$$I_H^2 = I^2 - I_1^2 \quad (2)$$

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DOI 10.1109/UKSim.2014.12

Voltage and current total harmonic distortion can be calculated as follows

$$THD_v = \frac{V_H}{V_1} = \sqrt{\left(\frac{V}{V_1}\right)^2 - 1} \quad (3)$$

$$THD_I = \frac{I_H}{I_1} = \sqrt{\left(\frac{I}{I_1}\right)^2 - 1} \quad (4)$$

The following equations can be used to calculate the different power quantities.

$$S = VI \quad (5)$$

$$S_1^2 = P_1^2 + Q_1^2 \quad (6)$$

$$S_N = \sqrt{S^2 - S_1^2} \quad (7)$$

$$N = \sqrt{S^2 - P^2} \quad (8)$$

$$P = P_1 + P_H \quad (9)$$

$$PF = \cos\phi = \frac{P}{S} \quad (10)$$

$$DPF = \cos\phi_1 = \frac{P_1}{S_1} \quad (11)$$

where

V, V_1 and V_H: total, fundamental and harmonic voltages, V
I, $I_1$and I_H: total, fundamental and harmonic currents, A
P: active power, W
P_1: fundamental active power, W
Q_1: fundamental reactive power, var
S: apparent power, VA
S_1: fundamental apparent power, VA
S_N: nonfundamental apparent power, VA
N: nonactive power, var
PF: power factor
DPF: displacement/fundamental power factor

III. HOME APPLIANCES MODELLING

The schematic diagram of the CLP model used to simulate the LCD TV, regular refrigerator and the ASD washer is shown in Fig. 1. It consists of four main blocks. The harmonics filter, Electromagnetic Interference (EMI) Filter, AC/DC rectifier and the load that is modeled using a Voltage-Controlled Current Source (VCCS).

The purpose of the harmonics filter is to help in shaping the current drawn by the CLP to be similar to the measured one and therefore gives same THDi and individual harmonics.

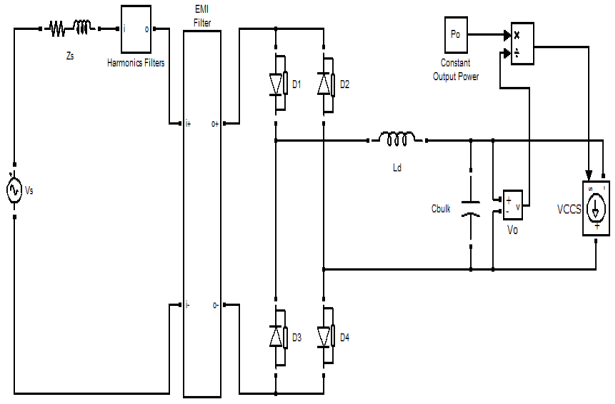

Figure 1. CLP model

A typical EMI filter configuration and design procedure are used with the assumption that an attenuation of 24dB/decade is required at the switching frequency [7, 12-15].

IV. MEASUREMENTS AND SIMULATIONS RESULTS

In this section, experimental measurements and simulation results of the LCD TV, regular refrigerator and ASD washer are discussed.

A. LCD TV

There are different types of TVs in the market such as LCD, CRT and Plasma. An LCD TV was chosen as it becomes one of the most widespread TV technologies in the world. As the LCD TV operates continuously, its operating power is almost constant. A 42" LCD TV was monitored and the harmonics and power quantities, spectrum and typical waveform can be shown in Table I and Figs. 2 and 3.

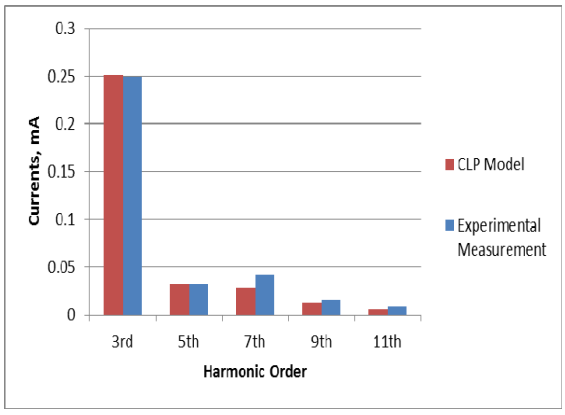

Figure 2. Current spectrum of the LCD TV

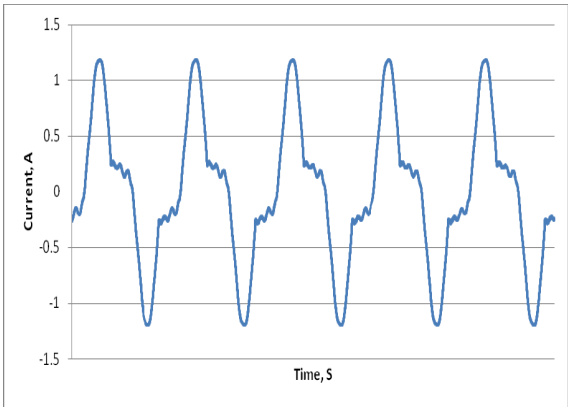

Figure 3. LCD TV current waveforms

TABLE I. LCD TV HARMONICS AND POWER QUANTITIES

Index	CLP Model	Experimental Measurement
%THD$_v$	0.039	0.059
%THD$_i$	42.83	42.96
1st, mA (%)	0.60 (100)	0.60 (100)
3rd,mA (%)	0.25 (42.03)	0.25 (41.70)
5th, mA (%)	0.033 (5.44)	0.032 (5.50)
7th, mA (%)	0.028 (4.76)	0.042 (6.90)
9th, mA (%)	0.013 (2.13)	0.016 (2.60)
11th,mA (%)	0.007 (1.09)	0.009 (1.60)
V,V$_{rms}$	239.85	239.703
I, A$_{rms}$	0.65	0.65
P, W	133.59	133.97
N, Var	80.55	80.94
S, VA	155.99	156.52
P.F.	0.856	0.856

It can be shown from Table 1 and Fig. 1 that the 3rd harmonic is by far higher than the other lower order harmonics as it is about 42% of the fundamental. The 5th and 7th order harmonics are about 5% while the other harmonics are 2% or less.

B. Regular Refrigerator

Regular refrigerators constitute the most common refrigerators within the residential sector. When a regular refrigerator was monitored, it was noticed that its operating conditions was either on or off. The harmonics and power quantities, spectrum and typical waveform of a small regular refrigerator during on condition can be shown in Table II and Figs. 4 and 5.

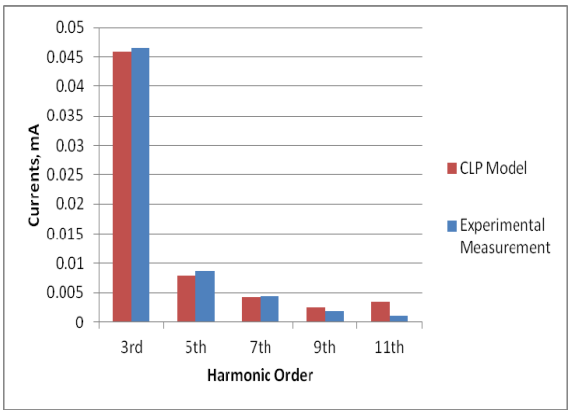

Figure 4. Current spectrum of the regular refrigerator

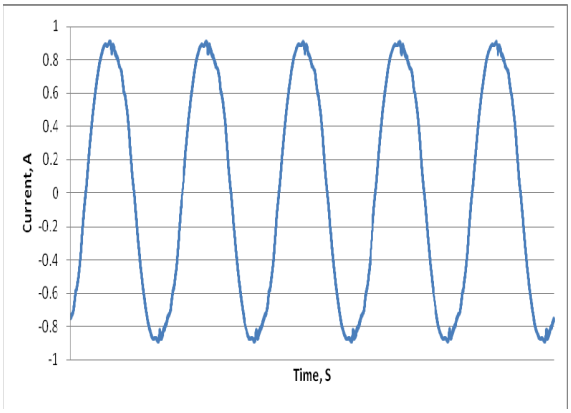

Figure 5. Regular refrigerator current waveforms

TABLE II. FRIDGE HARMONICS AND POWER QUANTITIES

Index	CLP Model	Experimental Measurement
%THD$_v$	0.017	0.043
%THD$_i$	7.17	7.17
1st, mA (%)	0.66 (100)	0.66 (100)
3rd,mA (%)	0.046 (6.91)	0.046 (7.0)
5th, mA (%)	0.008 (1.20)	0.009 (1.30)
7th, mA (%)	0.004 (0.64)	0.004 (0.70)
9th, mA (%)	0.003 (0.38)	0.002 (0.30)
11th,mA (%)	0.003 (0.52)	0.001 (0.20)
V,V$_{rms}$	239.88	239.70
I, A$_{rms}$	0.666	0.667
P, W	88.24	87.42
N, Var	133.30	133.97
S, VA	159.86	159.97
P.F.	0.552	0.546

Although the THDi of the regular fridge is fairly low about 7.17%, the current distortion is mainly due to the 3rd harmonic that is 7% of the fundamental. The 5th harmonic is slightly more than 1% while the rest of the harmonics are below 1%.

C. ASD Washer

When an ASD washer was monitored, it was noticed that it went through different operating conditions like filling water, washing, rinsing, and spinning. As rinsing consumes and injects the highest power and harmonics, the monitoring was done during this operating condition. The harmonics and power quantities, spectrum and typical waveform of an ASD washer are shown in Table III and Figs. 6 and 7.

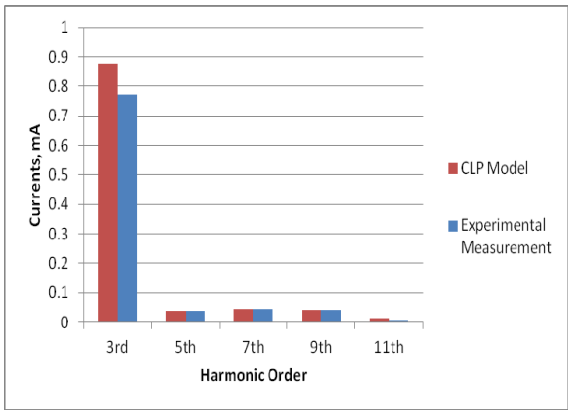

Figure 6. Current spectrum of the ASD washer

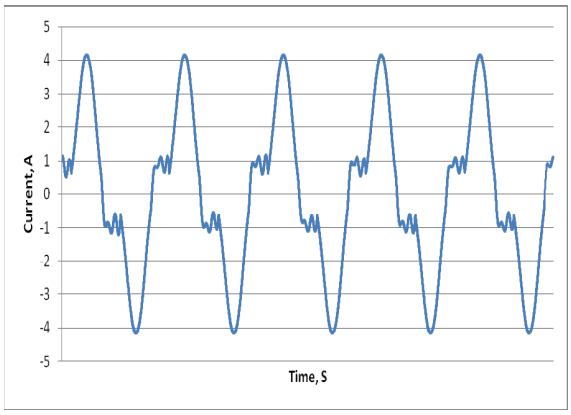

Figure 7. ASD washer current waveforms

Again the 3rd harmonic is the main contributor to the current distortion of the ASD washer as the THDi is about 41.14% and IHD$_3$ is 40.67%. While the rest of the harmonics are about 2% or less.

TABLE III. WASHER HARMONICS AND POWER QUANTITIES

Index	CLP Model	Experimental Measurement
$\%THD_v$	2.352	2.187
$\%THD_i$	41.14	41.14
1^{st}, mA (%)	2.153 (100)	1.894 (100)
3^{rd},mA (%)	0.88 (40.72)	0.77 (40.67)
5^{th}, mA (%)	0.04 (1.85)	0.04 (2.05)
7^{th}, mA (%)	0.044 (2.03)	0.045 (2.39)
9^{th}, mA (%)	0.043 (1.99)	0.043 (2.26)
11^{th},mA (%)	0.013 (0.61)	0.006 (0.31)
V,V_{rms}	235.04	233.49
I, A_{rms}	2.33	2.24
P, W	107.80	107.53
N, Var	536.46	538.42
S, VA	547.18	549.05
P.F.	0.197	0.196

It should be noted that the harmonics filter was used to shape the current waveforms of the loads considered in this research to be close to measurements. Notwithstanding, current waveforms can be different for different LCD TVs, regular refrigerators or ASD washers. Hence, this paper suggests that waveforms of any loads are measured first. Then, the CLP can be used with the help of the harmonic filters to simulate the behaviors of these loads precisely. This allows engineers and researchers to estimate the harmonics produced by these loads and assess their simultaneous effects on power systems accurately.

V. CONCLUSION

The proliferation of power electronics based nonlinear loads increases the harmonics level in power systems. Accurate modeling of these loads helps in assessing the distortion levels in distribution systems. Experimental measurements and simulation results of the LCD TV, regular refrigerator and ASD washer are presented and discussed.

As the harmonics generated by the CLP model gives close results to measurements, the CLP model can be used to simulate LCD TV, regular refrigerator and ASD washer.

Since LCD TVs, washers and fridges exist almost in all residential houses they are reasonably high harmonics producers. The results show that the LCD TV, regular refrigerator and ASD washer inject mainly the 3^{rd} harmonic current. Finally, both the LCD TV and ASD washer produces more harmonics than the regular refrigerator.

ACKNOWLEDGMENT

The authors would like to acknowledge King Abdulaziz University for their financial support of this PhD study.

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