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Keywords

Supply, current, characteristics, modern, domestic, loads

Disciplines

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Supply Current Characteristics of Modern Domestic Loads

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Abstract— The domestic load is considerably different to that seen 10 to 15 years ago. It has evolved significantly in terms of consumption and characteristics. In addition to traditional resistive and refrigeration type loads, the modern domestic load is now likely to contain a variety of sophisticated devices mostly powered and controlled by power electronics. This paper examines the power quality characteristics of the modern domestic load. Laboratory testing and mathematical analysis is used to quantify and predict the behaviour of loads operating individually and in parallel. Specifically examined is the behaviour and variation in harmonic current magnitudes across a variety of loads.

Keywords-power quality; domestic loads; harmonics; power factor

I. INTRODUCTION

The past decade has seen considerable changes to the domestic load in terms of demand magnitude and appliance characteristics. These changes now mean that the modern domestic load has the potential to have a significant impact on distribution network power quality levels. From a power quality viewpoint, possibly the most important development has been the proliferation of single phase devices powered by switch mode power supplies or other power electronic systems. An increasingly dominant load is the modern air conditioner. These devices are also supplied by power electronic inverters, whether they are single phase, or less commonly, three phase units. An additional change to the characteristics of the domestic load has been initiated by the Australian Federal Government's policy to ban incandescent light globes. In the short term, the result of this policy will be a significantly increased penetration of Compact Fluorescent Lamps (CFLs), a non-linear load, and the only currently viable alternative to traditional incandescent globes.

Residential electricity consumption accounts for 27.8% of the total electricity consumption in Australia [1]. While there have been significant changes to the domestic load due to technological advances, the modern domestic load still contains many of the traditional appliances seen a decade ago. Hot water heating still represents the major domestic load and accounts for up to 40% of domestic energy use [2]. Cooking and space heating also account for significant level of domestic energy use as does refrigeration. As of 2005, 99.9% of domestic residences had refrigerators [3], while 50% had air conditioners [2]. 2008 figures, available in [4],

put air conditioner penetration at 65%. The main differences between the domestic load today and that of a decade ago are the penetration and characteristics of electronic appliances such as computing and audio-visual loads, air conditioners and CFLs.

It is clear that the modern domestic load now comprises a significant proportion of non-linear devices which have the potential to lead to adverse power quality impacts on the electricity distribution network. The evolution of the residential load in terms of magnitude and characteristics into a significant distorting load and as such a potential source of significant power quality issues is worthy of detailed study. According to [5], up to 69% of the modern domestic load may now be comprised of non-linear loads. The effects of poor power quality on the distribution network and equipment connected to it can be varied and may be subtle, only becoming apparent over many years.

There has been a considerable number of studies including [6], [7] and [8] conducted which investigate the impact of consumer electronics on power system harmonic levels. However, the accuracy of these studies is heavily dependant on the characteristics of the models used to simulate the domestic loads. Many of these studies simplify domestic electronic loads by using waveforms characteristic of full wave bridge diode rectifiers. The results of the testing performed in this study indicate that this may be a simplistic assumption and may produce results which are unnecessarily pessimistic.

This paper examines the power quality characteristics of modern electronic domestic loads. The loads examined are those that have high penetration levels, have relatively high power demand and have evolved significantly over the last decade. For the purposes of this paper, the following loads have been examined: -

- Televisions
- Personal Computers
- Air Conditioners
- Lighting

While the authors accept that these loads do not cover the full spectrum of non-linear devices that may be found within a modern domestic residence, it is not practical to examine

every type of appliance. The devices listed cover the major non-linear loads in terms of penetration and power demand.

Where appropriate, comparisons are made between older technology and modern devices to demonstrate the evolution of load types. The power quality characteristics examined are harmonic current magnitude and phase angles and displacement power factor characteristics.

II. TESTING PROCEDURES

A combination of laboratory testing, field testing and mathematical analysis has been used to understand the behaviour of loads operating individually and with other loads.

For laboratory testing, the characteristics of each device have been examined for an undistorted 230 V supply voltage. In all cases, test voltages were applied using a California Instruments MX30-3PI programmable source. For undistorted waveforms, this device has a very low output voltage distortion level (~0.24% THD) and high magnitude accuracy.

It is cost prohibitive to obtain many different brands and types of loads for testing in a laboratory environment. Accordingly, some of the appliances examined in this study have had their characteristics monitored in the field. The drawback of this type of examination is that there is no control over the voltage supply waveform. The magnitude and background harmonic distortion of the supply voltage waveform will have some impact on the currents drawn by the device connected to it. In general, however, voltage magnitudes and background harmonic distortion levels in Australia do not vary to such an extent as to have a large impact on the characteristics of the current waveform drawn by the devices under test.

III. TELEVISIONS

There has been considerable development in television technology over the past decade. Traditional CRT type technology has been replaced almost exclusively by plasma and LCD technology. Commensurate with this has been a trend toward larger and larger screen sizes. There is considerable concern regarding the power quality implications of these devices as they generally consume far more active power than their predecessors [9]. Laboratory testing has been carried out on a 34 cm CRT television, a 51 cm CRT television and a 32 inch plasma screen.

Key parameters of RMS Current (I_{RMS}), Active Power (P), Apparent Power (S), Reactive Power (Q), Displacement Power Factor (DPF) and Current THD (I_{THD}) for each of the televisions tested are presented in Table I.

TABLE I. KEY PARAMETERS FOR TELEVISIONS

Parameter	34cm CRT	51cm CRT	Plasma
I_{RMS} (A)	0.29	0.53	0.50
P (W)	47.99	58.88	103.68
S (VA)	67.43	120.86	115.20
Q (Var)	47.36	-105.54	-49.60
DPF (- indicates leading)	-0.98	1	0.96
I_{THD} (% of fund)	94.17	178.21	34.03

The current waveforms of each television used in the laboratory tests are presented in Figure 1. Laboratory testing indicated that the plasma screen television has a significantly higher active power demand than the older style televisions. However, Figure 1 indicates that the concerns regarding higher harmonic current levels due to higher fundamental active power consumption may be unfounded due to the fact that the current waveforms for the CRT televisions appear considerably more distorted than the current waveforms for the plasma television. This is confirmed by the I_{THD} values in Table I and the data presented in Figure 2 which shows a comparison of the harmonic current spectra of the three televisions. It is clear that the harmonic currents drawn by the older style televisions are larger than those drawn by the plasma screen, both in terms of percentage of fundamental current and in terms of magnitude in amps, in spite of the higher fundamental power consumption of the more modern equipment.

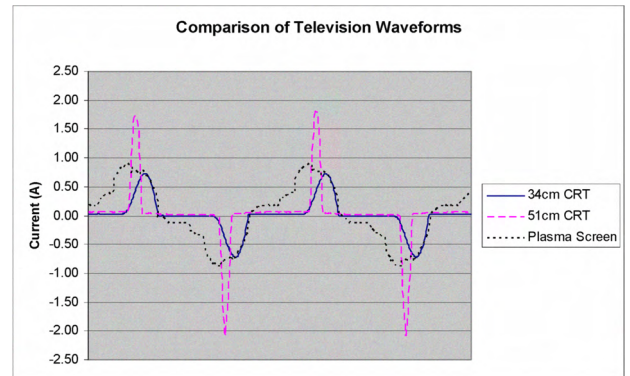


Figure 1. Comparison of Televisions Waveforms for Laboratory Testing

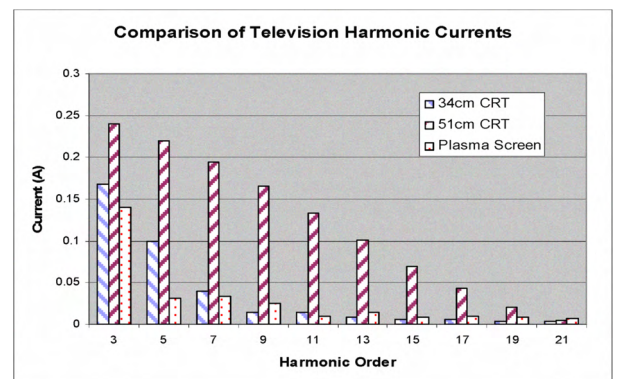


Figure 2. Comparison of Harmonic Currents Drawn by Televisions

For displacement power factor, Table 1 shows that all televisions tested had very high displacement power factors.

Field testing has also been performed on one CRT and two LCD televisions. The waveforms of these televisions, as shown in Figure 3, indicate that the performance of these devices is similar to those obtained for the laboratory tests described above. The CRT television is shown to have a significantly more distorted current waveform than the two LCD televisions. Comparing Figure 3 with Figure 1 it appears that the LCD televisions have a less distorted waveform than the plasma television. These results indicate that modern televisions may have better harmonic performance than their predecessors despite larger screen sizes and active power consumption.

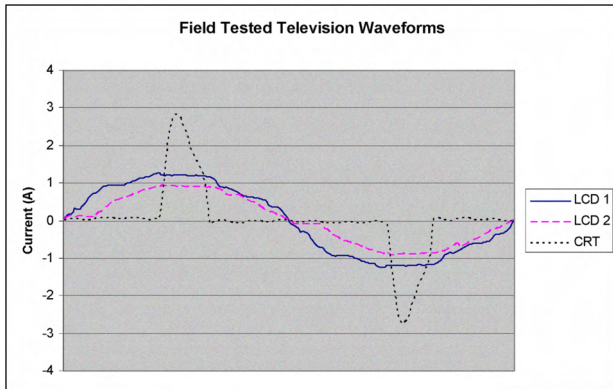


Figure 3. Field Tested Television Waveforms

IV. PERSONAL COMPUTERS

According to [3] the penetration of personal computers in domestic residences has risen from negligible levels in 1994 to 68% in 2005. Three computers have been laboratory tested for the purposes of this study. These are:-

- An older style Pentium 4 1.6Ghz desktop PC
- A more modern Pentium 4 dual core 3Ghz desktop PC
- A laptop PC

Figure 4 shows the current waveforms for each of the computers tested.

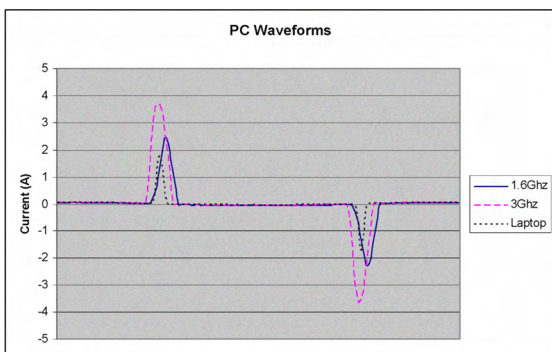


Figure 4. Waveforms for Laboratory Tested PCs

Figure 4 shows that the current waveforms drawn by the PC are similar in characteristics and are indicative of the waveforms drawn by traditional full wave diode bridge rectifiers. Table II shows the key parameters for the PCs tested.

TABLE II. KEY PARAMETERS FOR PERSONAL COMPUTERS

Parameter	1.6 Ghz	3 Ghz	Laptop
I RMS (A)	0.57	0.92	0.38
P (W)	58.64	94.12	28.17
S (VA)	130.87	212.07	87.71
Q (Var)	-117	-190.04	-83.05
DPF (- indicates leading)	1	-0.99	-0.94
I THD (% of fund)	196.49	198.73	264.49

The data in Table II shows that the PCs are characterised by highly distorted waveforms with current THD levels of approximately 200%. Displacement power factor levels are seen to be high and near 1 for all PCs tested.

V. AIR CONDITIONERS

Variable speed air conditioners are potentially the largest non linear load found in any domestic residence. Both the size and number of inverter driven air conditioners has grown substantially over the past decade. According to [2], the proportion of homes with electric air conditioning has grown by 32% in the decade to 2004. Penetration levels in some areas are in excess of 100%. Modern, split systems or ducted air conditioners range in size from approximately 2 kW up to approximately 14 kW and are almost universally inverter driven as these units are more efficient than traditional types. There has been considerable work, for example [6] and [7], which endeavours to assess the impact of variable speed air conditioners on the electricity supply network.

Traditionally, the current waveform of a variable speed air conditioner has been characterised as similar to the highly distorted waveform of a full wave diode bridge rectifier. Figure 5 shows an example of this from [10].

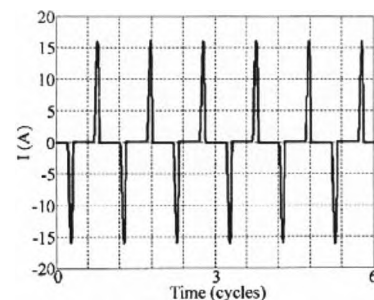


Figure 5. Current waveform for Variable Speed Air Conditioner [10]

A 3.3 kW variable speed air conditioner has been laboratory tested for the purposes of this study. The current

waveform drawn by this device is shown in Figure 6. It can be seen that the current waveform drawn by this air conditioner is considerably less distorted than that the current waveform shown in Figure 5. The current THD for the air conditioner tested in the laboratory was found to be 3.43% compared to 114% for the air conditioner examined in [10].

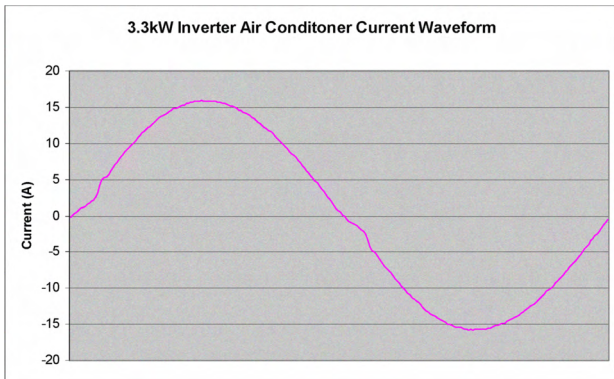


Figure 6. Laboratory Tested Variable Speed Air Conditioner Waveform

A second variable speed air conditioner has been tested in the field. The waveform for this air conditioner is shown in Figure 7.

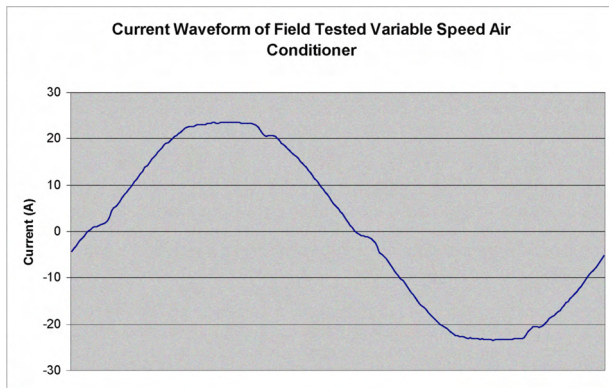


Figure 7. Current Waveform for Field Tested Variable Speed Air Conditioner

The similarity of the waveforms shown in Figures 6 and 7 indicate that the current waveforms of modern variable speed air conditioners may be significantly improved compared to those of older style variable speed air conditioners. This result will have a significant impact on the accuracy of studies which have been performed using air conditioner models characterised by current waveforms consistent with those shown in Figure 5.

VI. LIGHTING

The traditional lighting source for domestic residences has predominately been the incandescent light globe. The decision made by the Australian Federal Government to ban the use of traditional incandescent light globes by 2010 will see a dramatic change in the composition of domestic lighting load. Although LED technology is maturing, at present, the only viable alternative to the incandescent light globe is the CFL. The CFL is well known as a non-linear

load as identified in [11] and [12]. According to [5] lighting makes up 9% of the household electricity usage in NSW and although a significant energy saving will be achieved through the use of CFLs it may be at the cost of increased power quality problems.

A total of 25 different modern CFLs have been laboratory tested. These CFLs represent a range of brands, construction types and ratings from a cross section of suppliers and at a variety of price levels. All of the CFLs tested, with the exception of Lamp P, are standard non-power factor corrected types. Lamp P is a power factor corrected type CFL which contains additional components designed to mitigate harmonic currents. Table III lists the CFL globes which have been tested.

TABLE III. LIST OF CFLS TESTED

Reference No.	Construction (Spiral/Straight)	Nominal Rating (W)
A	Spiral	15
B	Spiral	8
C	Straight	15
D	Straight	14
E	Straight	11
F	Straight	20
G	Straight	11
H	Spiral	15
I	Straight	15
J	Straight	15
K	Straight	11
L	Spiral	20
M	Straight	15
N	Straight	11
O	Straight	15
P	Spiral	15
Q	Straight	11
R	Spiral	15
S	Spherical	20
T	Straight	11
U	Spiral	11
V	Straight	14
W	Straight	18
X	Straight	18
Y	Straight	10

The majority of CFLs tested were characterised by highly distorted current waveforms. Figure 8 shows a sample of the current waveforms measured, with the sinusoidal voltage waveform shown for comparison. It can be seen that there is considerable variation in the shape of the waveform drawn by these three different makes of CFL. The figure specifically shows the least distorted and most distorted current waveforms with the third waveform being something in between. The current waveform for Lamp P which has been designed to correct power factor by minimising waveform distortion is particularly distinct

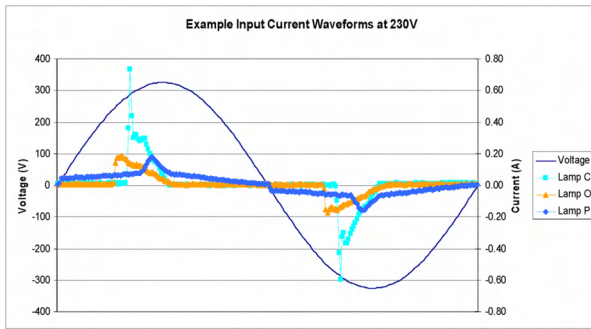


Figure 8. Selected CFL Current Waveforms

The appearance of the current waveforms in Figure 8 suggests that the input current of the CFLs will be rich in harmonics. This is confirmed by analysis of the harmonic current drawn by the CFLs. Figure 9 shows the measured Current Total Harmonic Distortion (I THD) for each CFL. It can be seen that all CFLs except Lamp P have ITHD levels close to or exceeding 100%. The maximum current THD level is 171% (Lamp Y). Figure 10 shows the harmonic spectra of the CFLs shown in Figure 8. Again, it can be seen that Lamp P has considerably better harmonic performance than the other two CFLs. Of particular note is the fact that the CFLs show harmonic currents of significant magnitude out to very high harmonic orders which is not characteristic of most domestic appliances.

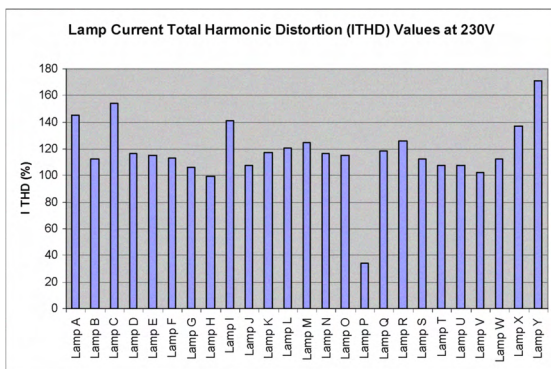


Figure 9. Current THD Levels for each Lamp

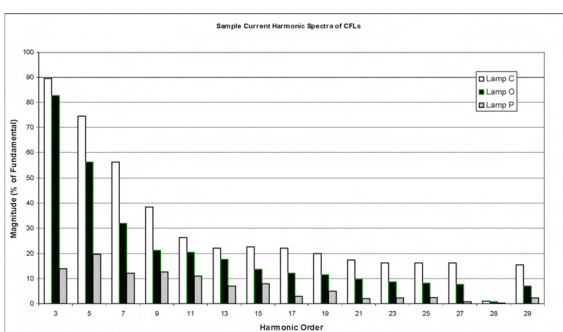


Figure 10. Sample Current Harmonic Spectrums for CFLs

Examination of the measured power factor levels of each CFL for displacement and true power factor respectively, indicates the following: -

- The displacement power factor of the CFLs is relatively high, averaging 0.89. The maximum is 0.98 for Lamp P, while the minimum is 0.81 for Lamp D. Displacement power factor is found to be leading in all cases. This suggests that the CFLs may provide some displacement power factor correction to the traditionally inductive residential load.
- The true power factor, calculated as active power/apparent power, for all CFLs with the exception of Lamp P is found to be poor, averaging, 0.58. The high true power factor of Lamp P, at 0.92, indicates the effectiveness of the power factor correction technology included in this CFL.
- The relatively high displacement power factor and poor true power factor associated with CFLs is due to harmonic and other non-fundamental components of current. This leads to apparent power levels considerably greater than active power levels.

VII. EFFECT OF LOADS OPERATING TOGETHER

This section of the paper attempts to identify which of the modern loads examined in the preceding section is the dominant harmonic load within a domestic residence. This section only examines the impact of the loads individually and the phase angle interaction has been ignored. As such, the true harmonic impact of the domestic load cannot be considered to be the sum of the harmonic currents for each device presented here. For the purposes of this analysis assumptions have been made regarding the numbers of each appliance operating simultaneously inside a domestic residence. The following are the assumptions that have been made:

- 2 modern televisions (plasma or LCD) operating simultaneously.
- 10 CFLs operating simultaneously. For CFLs the effects of three types of 15W CFL have been analysed; Lamp C, Lamp O and Lamp P from Section VI.
- 1 3.3kW variable speed air conditioner is operating.
- 1 PC is operating.

Figure 11 shows the fundamental current magnitudes based on the assumptions above. It can be seen that the air conditioner (AC) is the largest load in terms of active power demand. The CFLs, while only a small load individually, have a similar power demand as the other appliances if it is assumed that 10 are in operation simultaneously.

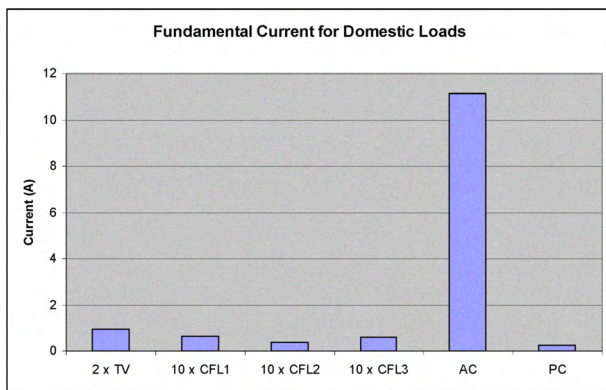


Figure 11. Fundamental Current Magnitudes for Assumed Appliance Mix

Figure 12 shows the harmonic currents drawn by each appliance or combination of appliances described above. It can be seen that while the air conditioner had the largest active power demand, it is not the dominant harmonic load. Instead, the 10 poor quality CFLs of type Lamp C are the dominant harmonic load, followed by the PC. The televisions are the load which is of least concern.

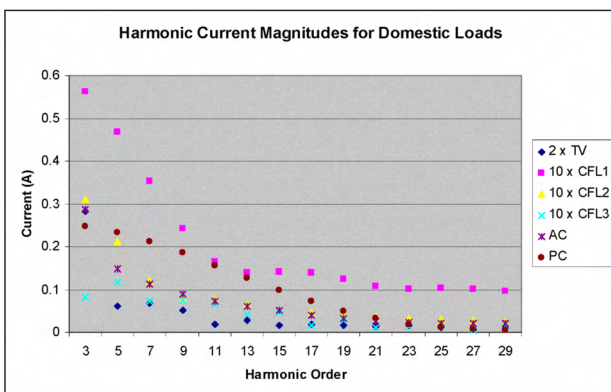


Figure 12. Harmonic Currents Drawn by Combination of Loads

VIII. CONCLUSIONS

This paper has investigated the power quality characteristics of the most common modern domestic loads. It is found that contrary to some popular opinion, the power quality characteristics of modern loads may not be inferior to those of their predecessor in spite of the fact that the modern devices have active power demands significantly greater than those that they are replacing.

For televisions, modern plasma and LCD types are found to have harmonic performance considerably better than that of older style CRTs in spite of the fact that the modern devices have active power demands significantly higher than the CRTs.

Similar results are observed for variable speed air conditioners with the modern generation of variable speed air conditioners having very good harmonic performance much better than the performance based on the assumption of current waveforms characteristics of simple full wave diode bridge rectifiers. The only loads found to accurately reflect

the assumption of a full wave diode bridge rectifier are power supplies for personal computers.

The lighting load is one which has seen considerable changes in characteristics the past few years. Incandescent globes are being replaced with CFLs. These CFLs have harmonic performance which is much worse than the linear behaviour of the traditional incandescent globe. This combined with the fact that many lights are often in operation simultaneously means that the modern lighting load must now be considered an important harmonic source.

Overall, the results presented in this study indicate that modelling the effect of domestic electronic equipment on the power system using load models based on simple full wave diode bridge rectifiers may be overly simplistic and will likely give results which are pessimistic.

These results presented in this paper of particular interest to distribution utilities who have a responsibility to maintain acceptable power quality levels on distribution networks and also to those seeking to accurately model the behaviour of modern domestic loads.

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