Electrical and Thermal Characteristics of Household Appliances: Voltage Dependency, Harmonics and Thermal RC Parameters

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Abstract

Detailed bottom-up load modelling of the residential sector has become increasingly important to examine the network impacts of both changing load composition due to the introduction of sustainable technologies, and changing load behaviour with increased levels of demand response. An important aspect of these models is the electrical and thermal behaviour of household loads. This paper examines the fundamental electrical and thermal characteristics of common household appliances. Methods to obtain the voltage dependency and equivalent resistive-capacitive (RC) circuit parameters for modelling thermostatically controlled appliances (TCAs) are presented. The paper also presents the results of laboratory experimental determination of voltage dependency coefficients, subjecting common appliances to a range of voltages within +/- 10% of the standard supply voltage. The thermal behaviour of TCAs are examined by use of thermocouples and plug-load monitoring devices. Appliances are grouped into into five distinct categories; lighting, motor, power electronic, resistive and wet appliance loads, and both their characteristics and operational behaviour is presented.

1 Introduction

It is increasingly important to be able to capture the thermal and electrical characteristics of household appliances for power system studies, in particular for the use of comprehensive bottom-up load models. These characteristics need to be constantly updated in an ever-changing load landscape, in particular with increasing drives for energy efficient appliances. Energy policy is currently driving appliance manufacturers to build more efficient appliances with lower power ratings. A notable example of this has been in the area of lighting, where the sale of certain incandescent light-bulbs were banned in 2009 by a directive by the European Union based on their low lumens per watt efficiency and high power consumption [1, 2]. Lighting in Ireland accounted for approximately 18% of average annual electricity consumption in the residential sector in 2008, [3], and given that power rating of more energy efficient compact fluorescent lights (CFLs) can be up to four times lower that that of incandescent lighting for similar lumen output, the directive stood to make significant energy savings. However, that transition could also have its own secondary effects. CFLs and light-emitting diodes (LEDs) have much lower power factors than that of incandescent, which, as they were impedance based, were close to unity. So this transition has led to a lower lighting load with significant capacitive power factors injecting reactive power into the network. These loads also have electronic ballasts which draw a current waveform with high harmonic content. Increasing levels of loads with power electronic interfaces can erode the traditional voltage and frequency response of the load and increase harmonic load current content which has potential impacts for power system operation.

Most appliances do not have perfectly in-phase sinusoidal load-current, in particular, power electronic devices have extremely non-linear current waveforms. With increased power electronics there is a significant risk of increasing harmonic content on the distribution network with the sources of harmonic injection becomes highly distributed and difficult to manage [4]. There are two main potential impacts of increasing levels of harmonic current, the first relates to three-phase four-wire systems. In a four-wire network, if the three phases are equally loaded the resultant neutral current will be zero due to phase cancellation. However, in the presence of triplen harmonics, the phase difference of 120° is cancelled as each phase produces harmonic current of identical phase. So triplen harmonic current content can exceed that of an individual phase by a factor of three, potentially leading to overloading on the neutral. The other main impact of high harmonic current is related to load and network equipment, problems which are increasingly prevalent with modern loads [5]. Excess harmonic content can both damage motors and can also interfere with many consumer electronics, particularly those sensitive to radio frequency. In terms of network equipment, harmonics can lead to increased eddy current losses in

*This work was conducted in the Electricity Research Centre, University College Dublin, Ireland, which is supported by the Electricity Research Centre's Industry Affiliates Programme (http://erc.ucd.ie/industry/). This material is based upon works supported by the Science Foundation Ireland, by funding Killian McKenna, under Grant No. SFI/09/SRC/E1780. The opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Science Foundation Ireland. Contact: killian.mckenna@ucdconnect.ie

distribution transformers, where the losses are proportional to the square of the frequency, f, increasing overall transformer losses, creating additional heat, and reducing transformer lifetime.

These potential impacts of harmonics mean that regulation of electromagnetic compatibility (EMC) is of crucial importance. Current EU directive on EMC, [6], repealed directive [7], regulating EU wide electrical standards in relation to electrical equipment and appliances. That directive refers to a range of standards for harmonizing legislation around EMC. Power factor correction standards legislate for appliances with a rated power of greater than 75 W to have power factor correction, with other power factor categories for lighting equipment [8]. As a result of this legislation many non-linear loads have had power factor correction (PFC) circuits included to satisfy harmonic limits [9]. Lighting loads over 25 W must adhere to the harmonic limits, with different harmonic limits for lower powered loads.

Another important factor is the voltage dependency of each load. Voltage varies throughout the day depending on both the loading and load composition at each time step, and closely follows the demand profile, with lower voltages during the day and higher voltages at night. Electrical appliances behave differently to changes in voltage, with a range of relationships between active power and voltage, ranging from constant with respect to voltage to a square relationship. Numerous laboratory studies to find the voltage dependency of household appliances have been conducted, and it is important that these studies are continually updated with an ever changing load landscape. In [10] laboratory measurements were conducted on a range of loads in Canada for assessing the impact of load models on voltage stability studies. A voltage dependent load component database for household and office appliances was developed in [11] using a polynomial model. Other load surveys on ownership statistics and voltage dependencies have been conducted for the UK, [12], using component based circuit modelling to find voltage dependency exponents for use in bottom-up load models [13]. In [14] the voltage variation on power and energy consumption for household appliances is investigated for 20 domestic appliances and the study showed standard power voltage relationships, but little reduction in energy consumption, and in some cases energy consumption exhibiting an inverse relationship with supply voltage for TCAs.

This paper focuses on obtaining electrical and thermal parameters of real domestic appliances using load monitoring techniques. For TCAs a method is presented to extract the thermal equivalent resistor capacitor (RC) circuit parameters. The extraction of this data allows for the thermal modelling of these appliances using discrete state-space representation. Thermal modelling is particularly important when considering loads that are thermostatically controlled, as these appliances have both inter and intra-temporal response to changes in supply voltage. In addition to capturing thermal characteristics, voltage dependency parameters which characterize the electrical behaviour of these appliances have also been obtained. The load monitoring and data obtained from this study is being used to improve a bespoke bottom-up load modelling tool that has been developed by the authors [15, 16]. For the purpose of simplification, the appliances here are broadly broken into five load categories, namely lighting, motors, power electronic, resistive and wet appliances.

The electrical and thermal studies herein were conducted in Dublin, Ireland, for which the distribution system operator (DSO) is ESB Networks. The nominal phase-to-neutral voltage is 230 V, with a tolerance band set by the DSO of +/- 10% [17]. In the distribution network, the primary substation, high-voltage/medium-voltage (HV/MV) transformer, typically has on-load tap-changing (OLTC) abilities, allowing it to regulate voltage to a prescribed band. The MV side of the primary substation is typically regulated to a reasonably high voltage, 1.045 per unit, to cater for voltage drop from the primary substation to most remote the end-of-line low-voltage (LV) customer. The secondary distribution transformer, MV/LV, is usually a manual tap changing transformer and DNOs can use this to operate seasonal Summer and Winter voltage taps.

2 Monitoring Equipment

The methodology presented here is for extracting electrical and thermal parameters based on measured data. For the electrical characteristics, extensive equipment is required in order to control supply voltage to examine voltage dependency and also to collect current waveform data at high frequency. Thermal characteristics can be captured by logging temperature data using thermocouples connected to digital multi-meter, and monitoring the electrical power concurrently using an energy monitoring socket.

2.1 Thermal Data Collection

A three-pin energy monitoring socket, capable of measuring operating voltage, current magnitude, active power and power factor, was used to monitoring the electrical consumption data whilst TCAs were in operation [18]. Two dual-channel digital thermometers with 2 K-Type thermocouple probes were used for the internal temperature monitoring, with two thermocouple probes monitoring internal temperature and two monitoring ambient temperature. For hard-wired appliances, a digital current-clamp multi-meter was used to measure the load current, and power was calculated assuming a supply voltage close to that of an available house socket.

2.2 Electrical Data Collection

Appliance electrical characteristic studies were conducted in the electrical engineering laboratory at University College Dublin. These studies involved subjecting a range of home appliances to a controlled variable single-phase voltage supply, over the DSO stated tolerance band of +/- 10%, in steps of approximately 1%, which corresponds to a voltage range of 207 V to 253 V. For low powered devices a 6 kVA variable transformer with a 10 A fuse was used along with a universal power analyser to measure the active and reactive power flows through the devices, and using differential probe to attenuate the load current, the appliance characteristic current waveform was analysed with a digital oscilloscope. For higher powered devices a 15 kVA variable transformer with a 75 A fuse was used. An inventory of the equipment used is in Table 1.

Table 1: Inventory of Laboratory Equipment.

Equipment:
6 kVA Variable Transformer, 0-400 V, 10 A Fuse
15 kVA Variable Transformer, 0-250 V, 75 A Fuse
PM300a Voltech Universal Power Analyzer
TA057 Pico Technology Differential Probe 1/200 & 1/20 Attenuation Ratios
MS07054A Agilent Technologies, InfiniiVision Mixed Signal Oscilloscope

3 Electrical Characteristics

At LV distribution network level many of the assumptions made at transmission level no longer hold. At high-voltage levels it can generally be assumed that the 3-phase systems are evenly loaded, current will be sinusoidal with low-harmonic current, and the load can be assumed to be almost independent of voltage. LV networks typically see much higher levels of harmonic current due to non-linear current waveforms and the load is extremely responsive to changes in voltage as there is no intermediate regulating transformer. The electrical characteristics discussed here are the analysis of non-linear current waveforms, where both displacement and distortion power factor need to be accounted for, along with harmonic content and voltage dependency.

3.1 Analysis of Non-Linear Current Waveforms

Power factor, or true power factor, for non-linear waveforms is a product of both displacement power factor and distortion power factor. This is represented in vector form in Figure 1, with P, Q, D, S_1 and S, which are active power, reactive power, distortion power, fundamental apparent power and total apparent power respectively. The angle φ_1 is the displacement angle between the input

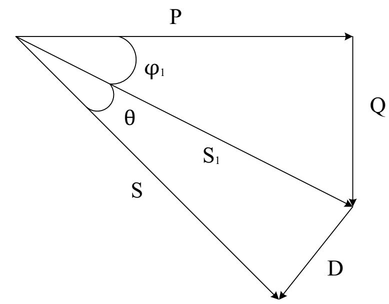

Figure 1: Vector Diagram of Complex Power with Harmonic Distortion

voltage and fundamental current component, and is the standard definition for power factor for a perfectly linear load with sinusoidal load current. The angle θ is the distortion angle and is a function of the harmonic content of the load current waveform, as θ approaches zero the total harmonic content decreases, and power factor becomes purely a function of the displacement angle of the fundamental harmonic.

By using load current waveform data, the current can be broken up into its constituent harmonics by using Fourier transform techniques. This allows for the isolation of the fundamental frequency component and the constituent harmonics, so that both the displacement, (1), and distortion power factor, (2), can be calculated using the root-mean square current and fundamental current component, $I_{RMS(total)}$ and I_{1RMS} respectively, and consequently the true power factor can be calculated, $P.F$, see (3).

$$\cos\varphi_1 = \left(\frac{P}{S_1}\right) \tag{1}$$

$$\cos\theta = \frac{I_{1RMS}}{I_{RMS(total)}} \tag{2}$$

$$P.F = \cos\theta\cos\varphi_1 \tag{3}$$

The load data captured by the oscilloscope is sampled at 50 micro-seconds, and for a duration of 2.5 cycles of the fundamental frequency, which for the power system on the island of Ireland is 50 Hz. For some of the data there is high frequency noise present which only occurred for signals for which a very high attenuation ratio was used on the differential probe. A first-order zero-phase low-pass digital filter was used to clean the data for which this very high frequency noise was present, the zero-phase characteristic of the filter used is important to preserve the phase of the original waveform needed to calculate the displacement power factor.

Using a Fourier transform of the original waveform we obtain the magnitude of each of the integer harmonics present, f_n, which are multiples of the fundamental frequency, f_0, see (4). From the Fourier transform the load current total harmonic distortion, THD_I, which is a measure of the harmonic content, can be calculated, see (5).

$$f_n = nf_0 \quad n \in \mathbb{N} \tag{4}$$

$$THD_I = \sqrt{\sum_{i=2}^{\infty} \left(\frac{\|I_i\|}{\|I_1\|} \right)^2} \tag{5}$$

Using the current total harmonic distortion power factor, THD_I, gives another approach for calculating the distortion power factor, $cos\theta$, see (6).

$$\cos\theta = \frac{1}{\sqrt{1 + THD_I^2}} \tag{6}$$

3.2 Voltage Dependency

The voltage dependency for active and reactive power can be described by the exponential load model equations in (7) and (8). Here P_0 and Q_0 are the nominal active and reactive power demand, V_0 is the nominal voltage and n_p and n_q are the active and reactive power voltage dependency exponents respectively.

$$P = P_0(\frac{V}{V_0})^{n_p} \tag{7}$$

$$Q = Q_0(\frac{V}{V_0})^{n_q} \tag{8}$$

Typically, power system loads are described in terms of three load types, each denoting an integer number in the exponential load model for active power, and shown for a 1 kW in Figure 2. These loads are defined as:

- Constant Impedance: These loads have a n_p equal to 2, and describe resistive loads. These are the most intuitive loads, as they describe a linear resistive element, $V = RI$, which exhibits a square relationship between active power and voltage, $P = \frac{V^2}{R}$. Thus any deviation away from the nominal active power can be described by equation (7) with n_p equal to 2. These type of loads are found in heating and cooking appliances, and approximately describe the behaviour of resistive lighting such as incandescent and halogen light bulbs. Active power is directly proportional to voltage, see Figure 2, as is current, so these appliances are ideal for responding to schemes such as conservation voltage reduction (CVR) where DSOs can operate their networks at reduced voltage in order to reduce demand.

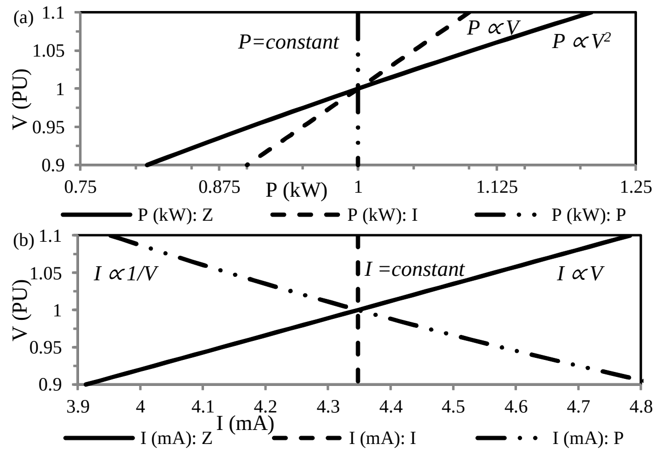

Figure 2: Power and current dependency on variation of per unit (p.u) supply voltage for a 1 kW load using constant impedance (Z), constant current (I) and constant power (P) load models.

- Constant Current: These loads have a n_p equal to 1. These loads have constant current, independent of voltage. These loads are still responsive to CVR, but will not result in reduced line current and hence network losses remain unaffected.

- Constant Power: These loads have a n_p equal to 0, and are generally representative of power electronic loads with switch-mode power supplies (SMPS). Constant power loads exhibit negative incremental impedance, meaning an increase in supply voltage leads to decrease in load current, or more significantly, decreases in voltage lead to increases in current. This inverse relationship can cause potential stability problems for power networks [19]. These type of loads cause strategies such as CVR to actually lead to worsening network conditions, as although power stays constant, load current increases leading to increased system losses.

By taking measurements of active power, reactive power and voltage it is possible to extract the voltage dependency exponents (9) and (10). It is prudent to take a range of measurements to validate the voltage dependency relationship, and the work in this study is conducted over the range of voltages from 0.9 p.u to 1.1 p.u in steps of 0.1 p.u, equating to a voltage range of 207 V to 253 V.

$$n_p = log_{(\frac{V_1}{V_2})} \frac{P_1}{P_2} \tag{9}$$

$$n_q = log_{(\frac{V_1}{V_2})} \frac{Q_1}{Q_2} \tag{10}$$

The alternative representation of voltage dependencies of loads is through using a composite polynomial model, which represents loads in terms of their constant impedance, constant current and constant power components, see (11) and (12). Using a composite model uses constant impedance, constant current and constant power parameters for active power, Z_P, I_P and P_P, and for reactive power, Z_Q, I_Q and P_Q, respectively.

$$P = P_0 \left[Z_p \left(\frac{V}{V_0}\right)^2 + I_P \left(\frac{V}{V_0}\right) + P_P \right] \tag{11}$$

$$Q = Q_0 \left[Z_Q \left(\frac{V}{V_0}\right)^2 + I_Q \left(\frac{V}{V_0}\right) + P_Q \right] \tag{12}$$

Obtaining the Z_P, I_P and P_P, and Z_Q, I_Q and P_Q, parameters through measurements involves obtaining, at minimum, three sets of measurements at different voltages, by virtue of having three unknowns resulting in the need for three equations. For simplification of the notation of these equations it is less cumbersome if voltage, V_{meas}, and active power, P_{meas}, are represented in per unit values (13, 14), and is presented here for the active power case as the reactive power case is analogous.

$$P_{meas,n} = (\frac{P_{meas}}{P_0}) \tag{13}$$

$$V_{meas,n} = (\frac{V_{meas}}{V_0}) \tag{14}$$

Taking the composite polynomial load model equation, (11), for each of our three cases results in a set of three equations with three unknowns. These can re-arranged to solve for Z_P, I_P and P_P using the three sets of measurements, see equations (15-17) respectively. Again, the reactive power case is analogous to the presented formulation below and the parameters for its dependency calculated in the same manner.

$$Z_P = \frac{P_{3n} - P_{1n} - \left(\frac{P_{2n}-P_{1n}}{V_2-V_1}\right) V_{3n} - \left(\frac{P_{2n}-P_{1n}}{V_2-V_1}\right) V_{1n}}{V_{3n}^2 - V_{1n}^2 + \left(\frac{V_{1n}^2-V_{2n}^2}{V_{2n}-V_{1n}}\right) V_{3n} - \left(\frac{V_{1n}^2-V_{2n}^2}{V_{2n}-V_{1n}}\right) V_{1n}} \tag{15}$$

$$I_P = \frac{P_{2n} - Z_P V_{2n}^2 - P_{1n} + Z_P V_{1n}^2}{V_{2n} - V_{1n}} \tag{16}$$

$$P_P = P_{1n} - Z_P V_{1n}^2 - I_P V_{1n} \tag{17}$$

The load model parameters can be calculated for each set of data points collected. Non-linear least squares regression analysis can be used to fit parameters for the range of data collected and this has been commonly used in the literature as a curve fitting technique for load models [20, 10, 11]. Genetic algorithms have also been used to fit load model parameters from power flow measurement data [21].

4 Thermal Characteristics

Many appliances in the residential sector are used for heating and cooling purposes and as such their thermal characteristics are extremely important to capture from a modelling perspective. These appliances can either operate to reach a temperature set-point, such as a kettle or storage heater, or to regulate temperature over a given time period, such as an oven or an electric space heater with thermostatic controls. This section details how to create an equivalent electrical circuit, made up of a single resistance and capacitance, that can describe the operation of these devices.

4.1 Calculation of RC Parameters

The RC parameters represent the thermal resistance, R_{th}, and the thermal capacitance, C_{th}, of the appliances. In reality a single appliance is composed of a who host of materials, each with there own thermal properties, that equates to a complete RC network. For the purposes of this work these appliances are simplified into a single equivalent RC model. The individual properties of material thermal capacitance, C_{th}, and the thermal resistance, R_{th}, can be calculated in (18) and (19). These values can then be used to calculate the time constant, (20), that represents the dynamics of the RC model at the point of the regulation thermostat. Calculations of this nature requires data on the thermal conductivity of the insulating material, κ, its thickness, x, and the total area, A, mass, m, and specific heat capacity, c_p.

$$R_{th} = \frac{x}{\kappa A} \tag{18}$$

$$C_{th} = mc_p \tag{19}$$

$$\tau = C_{th} R_{th} \tag{20}$$

Using the RC model, temperature evolution can be simulated using a discrete time-difference equation, which is a basic discrete state space representation, see equation (21). This representation has been commonly used in the literature for representing thermostatically controlled appliances [16, 22]. Here, T_a is the temperature of the body of mass being controlled, T_{amb}, is the ambient temperature, the time step in hours, h, the coefficient of performance, COP_a, for each appliance, a, which is set to 1 for those which are not heat pumps, the electrical power input is, $P_{elec,a}$, θ_a is the temperature gain

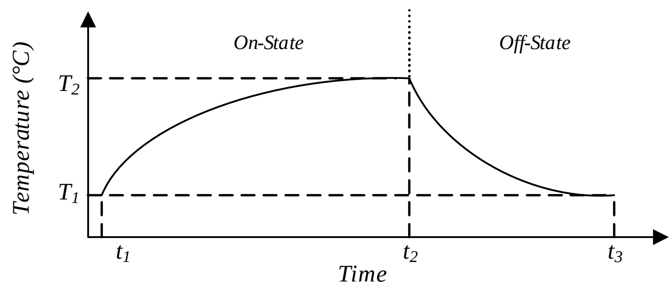

Figure 3: RC Parameter Estimation for a heating load from On-State and Off-State.

and $Y_a(t)$ is the binary control variable. The temperature gain, θ_a, for each appliance is calculated using equation (22).

$$T_a(t+1) = e^{-h/\tau}T_a(t) + (1 - e^{-h/\tau})(T_{amb}(t) - Y_a(t)\theta_a) \tag{21}$$

$$\theta_a = COP_a P_{elec,a}(t) R_{th,a} \tag{22}$$

4.2 Estimating Appliance Thermal Parameters

An alternative solution to calculating the RC parameters using a bottom-up approach is to conduct some basic load monitoring. Assuming that ambient temperature and electrical power input are constant, and taking two separate sets of measurements, the RC parameters can be obtained from two equations with the two unknown parameters, see Figure 3. This can be conducted by taking two sets of measurements, one for when the appliance is on, either using its electrical input to warm up or cool down is body mass, and a second set when the appliance is on the off-state. A range of measurements and data points across the temperature evolution of the device can be used to calculate a more robust set of RC parameters, and again, as per curve fitting for voltage dependency data, non-linear least-squares regression analysis can be used to fit the parameters.

4.3 Off-State: Time Constant Estimation

The discrete state-space representation describing the internal temperature evolution of an appliance with no thermal input can be described by equation (21). If ambient temperature is assumed constant, and two discrete temperature readings in time, T_{start} and T_{final}, with a time interval between these readings of δ, the relationship between those parameters can be described by equation (23). This equation can be re-arranged to solve for the time-constant of the appliance, see equation (24).

$$T_{final} = e^{-\delta/\tau}T_{start} + (1 - e^{-\delta/\tau})(T_{amb}) \tag{23}$$

$$\tau = \frac{-\delta}{log(\frac{T_{final}-T_{amb}}{T_{start}-T_{amb}})} \tag{24}$$

4.4 On-State: Thermal Resistance Estimation

When the appliance has thermal input to regulate the internal temperature, the system can be described by equation (21). Again, taking two discrete temperature readings in time with a time interval between these readings of δ, the system can be described by equation (25). This can be re-arranged to solve for the thermal resistance, using the time constant from the previous step, see equation (26). Finally, given the the time constant and the thermal resistance of the appliance, the thermal capacitance can be found, equation (27).

$$T_{final} = e^{-\delta/\tau}T_{start} + (1 - e^{-\delta/\tau})(T_{amb} - RP_{elec}) \tag{25}$$

$$R = \frac{T_{final} - T_{amb} + e^{-\delta/\tau}(T_{amb} - T_{start})}{e^{-\delta/\tau}P_{elec} - P_{elec}} \tag{26}$$

$$C = \frac{\tau}{R} \tag{27}$$

5 Results & Discussion

The active power and power factor of a total of 30 plug-in loads, 12 light-bulbs and the current-data for 4 hard-wired appliances were monitored as part of this study. For the voltage dependencies and waveform analysis a total of 18 plug-in loads and 10 light-bulbs were monitored. Furthermore, the temperature evolution and control of 12 thermal appliances were monitored. The loads analysed are broken into five distinct categories; lighting, motor, power electronic, resistive and wet appliances.

Some of the heating type appliances appeared not to regulate temperature and are included herein. These included toasters, hair-dryers and hobs, whose electrical consumption appeared to be independent of temperature. Active power consumption for toasters and hair-dryers was constant for the duration of operation, and electrical hobs maintained a constant duty cycle which was independent of surface hob temperature, and some

Table 2: Temperature Control of Household Thermal Appliances.

Appliances:	Temperature Control		
	Thermostat Control	Duty Cycle	Maximum Temperature Sensor
Refrigerator:	x		
Freezer:	x		
Kettle:	x		
Iron:	x		
Toaster:			x
Cooking Hob:		x	x
Oven:	x		
Hair Dryer:			x
Electric Shower:	x		x
Storage Heater	x	x	x
Space Heater	x	x	x

appliance control strategies varied per manufacturer, see Table 2. For example, electric hobs and some space heaters are operated using a combination of duty cycle operation and maximum temperature safety settings which automatically turn-off these appliances once they reach temperature threshold, whilst other space heaters are controlled thermostatically. Any device with duty cycle/set time operation typically has a maximum temperature sensor for safety purposes, and some appliance types can either be duty cycle or thermostatically controlled.

5.1 Lighting

There are four main lighting technologies in use in the residential sector, those being incandescent, halogen, fluorescent, and light-emitting diodes (LEDs). As previously mentioned, incandescent bulbs have been phased out in many countries, including Ireland, so the remaining light-bulbs are a legacy of before the ban and will continue to deplete till they have been completely replaced. Both incandescent and halogen bulbs have low efficacies (lumen/watt), with incandescent bulbs having a reported efficacy as low as 14.8 lm/W, with halogen slightly higher at 19 lm/W [23]. These bulbs exhibit resistive characteristics and reach high-temperatures when in operation, with most of their consumed electrical power being converted into heat. Fluorescent and LED lamps have much higher efficacies, typically greater than 60 lm/W, and fluorescent is starting to dominate the domestic lighting sector and accounted for over 23% of the UK domestic bulbs as of 2012 [24].

In the household monitoring study, the majority of bulbs were CFL, with no incandescent lighting in use. The bulbs monitored had low power ratings and power factors typically around 0.6, these were presumed to be capacitive, injecting reactive power, this was later confirmed by analysing the displacement power factor from the load current waveforms. Halogen was the next most dominant lighting source, with these exhibiting close to unity power factor and having higher power ratings. A result of varying supply voltage for lighting is that the lumen output is highly power dependent, and hence can be highly voltage dependent, meaning small changes in supply voltage can have a large impact on lighting output particularly for incandescent and halogen lighting.

- Incandescent Lighting

Incandescent lighting behaves close to a linear resistive circuit element, with sinusoidal load current, and theoretical square relationship between power and voltage. The active power voltage dependency exponent was found to be 1.52, see Table 3, closer to a constant impedance type load. These bulbs exhibited unity power factor, consuming negligible reactive power. Inside an incandescent bulb is a conducting filament, with the glass bulb containing an inert gas, mainly argon, but with some nitrogen type bulbs. The filament, usually tungsten, is heated to over 2500 °C so that it glows with white light, and the very low bulb efficacy results in the generation of a large amount of excess heat.

- Halogen Lighting

Halogen lighting should also have a theoretical voltage dependency close to that of an incandescent bulb, and in laboratory testing exhibited a sinusoidal load current. A problem with standard incandescent light bulbs is that evaporated tungsten deposits on the inner surface of the bulb resulting in bulb blackening and weakening the filament. Using halogen gas, a reversible chemical reaction is set up where the tungsten is released back to the filament at high temperatures. In laboratory experiments, halogen active power voltage dependency was found to be 1.56, and had a high, but not unity power factor in the range of 0.85-0.9 inductive, see Table 3.

- Fluorescent Lighting

Fluorescent lights consist of glass containing a low pressure gas such as mercury vapour. As current passes through this gas, the vapour becomes charged and electrons in the excited-state emit ultraviolet (UV) radiation. The UV radiation strikes a phosphor coating on the inner surface of the bulb, causing the phosphor to fluoresce, emitting white light. Compact fluorescent lamps (CFLs) have grown in popularity in the residential sector due in combination to both the ban on incandescent lighting, but also due to their longer lifetimes and energy efficiency. These lamps have electronic ballast with rectifier circuits to convert AC to DC, a filter capacitor and switching transistors. The switching transistors convert the DC to high frequency AC, usually these bulbs also have some built in power factor correction (PFC). The current waveform of CFLs is highly non-linear, with low

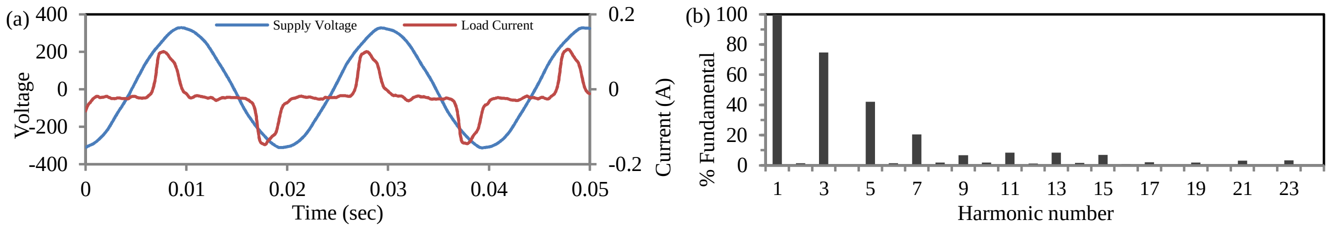

Figure 4: (a) Supply voltage and load current, and (b) Fourier Transform frequency components and magnitude for a CFL bulb.

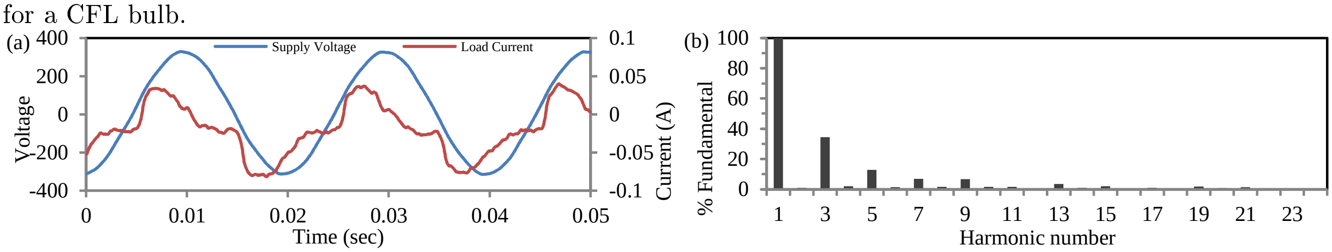

Figure 5: (a) Supply voltage and load current, and (b) Fourier Transform frequency components and magnitude for a LED lamp.

power factors and large harmonic distortion, with strong presence of triplen harmonics, see Figure 4. Although the voltage dependencies of these bulbs varied significantly, in a broad sense they were closest to constant current loads, see Table 3.

Table 3: Lighting Voltage Dependencies.

Bulb Type:	Power (Watt)	P.F	n_p	n_q	$\cos \psi$	$\cos \theta$	THD_I (%)
Incandescent 1	60	1	1.52	-	-	-	-
Incandescent 2	40	1	1.52	-	-	-	-
Halogen 1	25	0.9	1.56	3.12	-	-	-
Halogen 2	14	0.85	1.57	2.56	-	-	-
CFL 1	8	0.6	1.34	1.57	0.74	0.81	90.93
CFL 2	12	0.58	0.6	0.94	-	-	-
CFL 3	11	0.55	0.61	1.16	-	-	-
LED 1	7	0.67	0.01	1.39	0.93	0.72	40.93

- Light-Emitting Diodes

LEDs are based on solid-state technology and work on the principle of applying a voltage across a PN-junction causing electron recombination which results in the emission of photons of light when the device is conducting. LEDs typically have very high efficacy when compared to traditional light technologies, and they typically range between 50-70 lm/W. These lights typically have very low capacitive power factors, with available research giving power factors ranging between 0.46 and 0.72, [25], they also have very high-levels of harmonic current due to the highly non-linear current waveform due to the required AC/DC converter, see Figure 5. Due to the AC/DC converter these lights behave close to a constant power load, with active power voltages being close to zero, meaning power consumption is almost independent of supply voltage, see Table 3.

5.2 Motors

The majority of motors loads in the residential sector are single-phase split-phase induction machines (SPIM). These motors are found in refrigeration units, vacuum cleaners, hair dryers and other motor loads. SPIM motors are self-starting by providing an additional flux, to overcome high-starting torque. They have two windings, the main winding / running winding and an auxiliary winding / start winding, with a centrifugal switch to disconnect the start winding when the motor is close to synchronous speed. The running winding is inductive in nature. Split phase induction motors have low starting current and moderate starting torque so are used in residential motors such as fans, blowers, pumps, washing machines, etc. Capacitive start, capacitive run (CSCR) motors do not have a centrifugal switch, so the capacitor remains in the circuit and helps improve power factor. They have a high starting torque and are used in devices such as vacuum cleaners and wet appliances.

5.2.1 Electrical Characteristics

There are a range of different control schemes for motor loads, and each impacts the electrical characteristic of the device. Figure 6 shows the relationship between the different suction settings on a vacuum cleaner and their corresponding load currents. These motors typically use a Silicon Controlled Rectifier (SCR) circuit, with the fir-

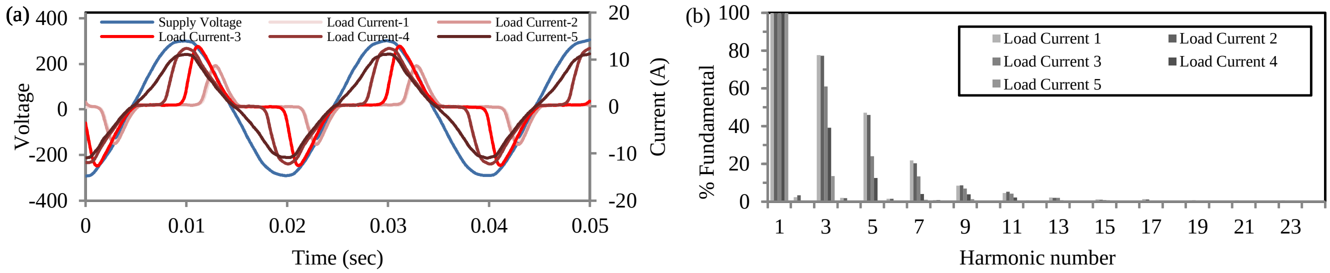

Figure 6: (a) Supply voltage and load current, and (b) Fourier Transform frequency components and magnitude for a vacuum cleaner at different suction settings.

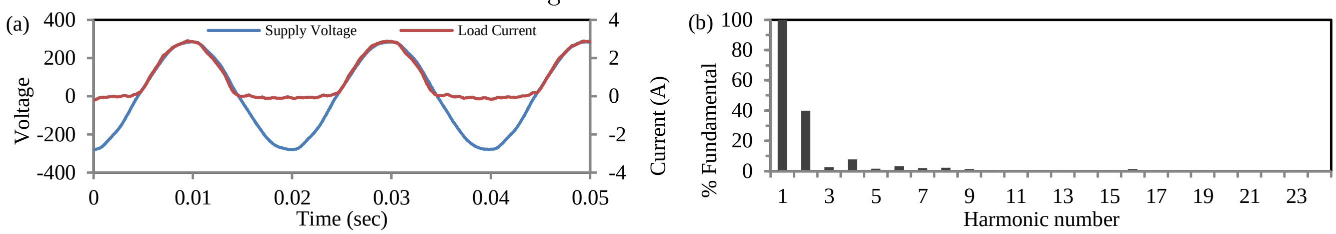

Figure 7: (a) Supply voltage and load current, and (b) Fourier Transform frequency components and magnitude for a hair dryer at lowest air setting.

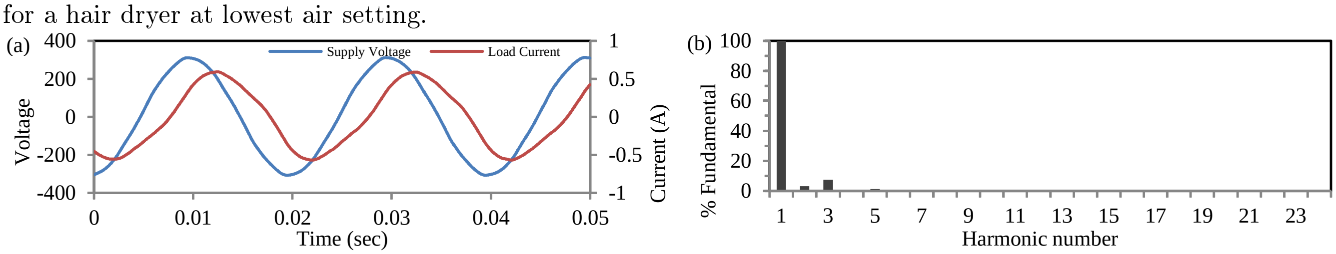

Figure 8: (a) Supply voltage and load current, and (b) Fourier Transform frequency components and magnitude for a refrigerator.

ing angle, or trigger pulse, of the rectifier circuit controlling how much power is delivered to the device [26]. Accordingly, the power factor of the device is a function of the length of time current is allowed to conduct, and consequently the firing angle. This means that at low power operation the power factor of these devices was as low as 0.43 inductive in tests, but improved as device active power was increased approaching unity power factor. This form of operation also impacts the harmonic current composition of the load current waveform, with a THD of the current waveform as high as 95% for low power operation, and decreasing to 14% for when the firing angle allows for full conduction.

A simpler form of motor control is a two-rate setting, by using both half and full-wave rectification. This setting can be found in a two air-setting hair dryer [27]. A DC motor drives the fan in the device and has two different speeds depending on whether the circuit is in half-wave or full-wave rectification. This also impacts the power factor and harmonic current content of the device, with greater harmonic content when the device is in half-wave, with a particularly high amplitude second harmonic, see Figure 7, than full wave operation. The heating elements of these devices are connected in parallel, energizing each branch of the resistive elements as more heat is required. The electrical characteristic of an appliance such as a hair dryer depends on the mode of operation, as it is a combination of a DC motor with power electronic interface and a series of resistive elements in parallel using a combination of each depending on the mode of operation. When both the resistive and motor elements of the device are in operation, the electrical characteristics of the resistive element dominates due to its significantly higher power consumption.

Refrigeration appliances are a major component of base load in the residential sector, and they use SPIM motors. These motors are used to run the refrigerator compressor which is operated based on the internal thermostat settings, which are regulated on a hysteretic cycle. These motors have quadratic torque with respect to motor speed and use a CSCR configuration due to the high starting torque [9]. Many residential motor appliances can have an initial current which can be 5 to 6 times that of normal operation, which is particularly relevant for cold-load pick-up [28]. Refrigeration units typically have low power factors due to the inductive nature of the motor, resulting in an inductive sinusoidal phase shifted load current waveform due to the AC nature of the motor and the required reactive power consumption, see Figure 8. However, the low power factor is mainly a product of high displacement power factor rather than distortion, as these devices typically have low levels of harmonic content, see Table 4. A simple cooling fan also has a similar AC load current waveform, as these are also basic SPIM motors.

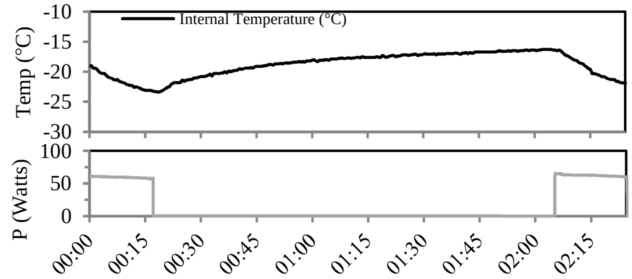

Figure 9: Active power (P) and temperature evolution of a domestic freezer.

Table 4: Motors Loads Electrical Data & Voltage Dependencies.

Appliance	Power (Watt):	P.F	n_p	n_q	$cos\ \psi$	$cos\ \theta$	THD_I (%)
Fan	40	1	1.5	2.6	-	-	-
Fridge	50	0.6	0.5	2.3	0.7	1	15.22
Hair Dryer (Fan)	200	0.7	2	2	0.8	0.9	41.23
Vacuum Cleaner	390	0.4	8.9	4.2	0.5	0.7	95.1
Vacuum Cleaner	1400	1	1.9	1.7	1	1	13.83

Table 5: Motor Loads RC Data.

Appliance:	RC (hours)	R_{th} (℃/kW)	C_{th} (kWh/℃)	Rating (kW)
Fridge	7.92	763.75	0.01037	0.07
Freezer	3.47	1749.52	0.00199	0.06

The active power voltage dependencies of motors loads varied hugely. There were principally two types of motors under investigation, which were were DC motors and AC motors, typically induction machines. DC motors require AC/DC converters, and those tested were hair-dryers and vacuum cleaners. Furthermore, as these motors could be controlled at different settings, active power, power factor and voltage dependencies also varied with operation, see Table 4. Two appliances investigated used induction motors, these were refrigeration units and fans, there were no clear voltage dependency characteristics for these devices.

5.2.2 Thermal Characteristics

The only set of motors that operated under thermostatic regulation in this study were refrigeration appliances. The internal temperature of these appliances were monitored in order to make an estimate of their thermal characteristics.

The RC constant of refrigerator loads were, as expected, quite high and in the order of hours, due to the high levels of insulation and thermal capacitance of these appliances, see Table 5. Refrigeration appliances operated within a thermostatic dead-band of 1 °C - 2 °C, whereas freezer appliances had a larger dead-band that was in the range of 4 °C - 5 °C, see Figure 9. A useful feature of extracting the RC constants of a refrigerator from the temperature evolution data is that the actual co-efficient of performance (COP), as a fridge is a heat pump, is embedded in the estimated thermal resistance, R_{th}, value. This is important as otherwise the COP would have to be calculate separately, which can be challenging particularly given non-ideal behaviour.

5.3 Power Electronics

There are increasing levels of power electronic loads in the residential sector, and these are particularly prevalent in the information communication technology (ICT) and consumer electronics (CE) product sector, however, as previously mentioned, they are also required in the operation of DC motors. The vast majority of these consumer electronics use a switched-mode power supply (SMPS), converting AC to DC. These appliances also tend to be low in power, with many beneath the 75 W level meaning they do not fall under power factor EMC standards. As a result, low powered consumer electronics tend to have very low power factors and high levels of harmonic content, as is illustrated in both the laboratory experiment and household survey of appliances. Those appliances which are above the 75 W level threshold fall under EMC standards, and have close to unity power factor due power factor correction standards.

The power electronic devices in the residential sector are used to perform a vast array of tasks and functions, furthermore power levels can rapidly change when in operation. This must be taken into account when determining the voltage dependencies of these devices, for instance, the active power draw of a radio is a function of not only volume, but the radio wave content coming in. In order to accurately perform voltage dependency tests it is then important to isolate a single function, for example getting a radio to play a single tone, displaying a blank screen on a television or having a laptop on standby. The load current waveform for these devices are almost identical, as they all use a very similar AC/DC interface to power the internal appliance circuit.

Table 6: Power Electronic Loads Electrical Data & Voltage Dependencies.

Appliance	Power (Watt):	P.F	n_p	n_q	cos ψ	cos θ	THD_I (%)
Radio	4	0.5	0.1	0.4	0.7	0.7	163
CD Player	11	0.6	1.6	2.4	-	-	-
TV	16	0.6	-0	0.8	1	0.6	136.4
DVD Player	9	0.6	0.3	-3	0.9	0.6	134.5
Games Console	16	0.5	0.1	0.2	-	-	-
Printer	5	0.4	0.3	0.6	-	-	-
Phone Charging	4	0.3	-0	0.1	-	-	-

Figure 10 and Figure 11 show the load current and harmonic content of a laptop and television respectively, which are characteristic of the typical load current for power electronic devices. The current waveforms and harmonic content for most consumer electronic appliances are almost identical, as fundamentally they all have the same initial stage AC/DC conversion.

5.3.1 Electrical Characteristics

The active power consumption of power electronic devices is almost independent of supply voltage, meaning they exhibit negative impedance characteristics. A decrease in supply voltage will result in an increase in load current. The voltage dependencies of the power electronic appliances under investigation were typically quite low, which was as expected given their constant power type characteristics, see Table 6.

As many of the devices under investigation were very low-powered, under existing legislation power factor correction is not required, resulting in low power factors. This is mainly due to high levels of harmonic content, with THD for some appliances reaching in excess of 130%. Power electronic devices above 75 W would have passive or active power factor correction, however none of the power electronic devices surveyed here were above that rating.

5.4 Resistive

The vast majority of cooking, space and water heating appliances have basic resistive elements that emit heat when conducting current. Some of these appliances have an internal thermostat, typically a bi-metallic strip, that is used to monitor internal temperature and control the load current. A simple example is that of a kettle, which has a resistive element that heats up a body of water to 100 °C. The internal thermostat measures the temperature of the body of water and switches off the circuit to the resistive heating element once the target temperature has been achieved. The power of an ideal resistive element is proportional to the square of the voltage, so these appliances are the most responsive to changes in supply voltage.

Some resistive based appliances do not monitor internal temperature. In toasters, the user decides the time for which the appliance will stay in operation, and the device will operate at full power until the time has elapsed, or the appliance exceeds a maximum temperature threshold, in which case the appliance will shut off for safety reasons [29]. Many electric cooking hobs and space heaters operate on duty-cycle based control, where the user setting determines the ratio of time between on and off operation [30]. This has been observed in the monitoring of household electric cooking hobs and some space heaters, where the on and off times remained constant and were controlled by a consumer operated dial, with duty cycle being independent of appliance temperature. In these devices positive temperature coefficient (PTC) thermistors are frequently used to automatically shut off these appliances in cases of over-heating.

Appliances with specific temperature set-points are controlled thermostatically, with temperature regulation around a thermostatic dead-band. This has been observed in ovens and some space heaters. For household ovens, the internal temperature was monitored and as devices are typically hard-wired a current-clamp multimeter can be used to estimated their power consumption. Oven appliances have both resistive and motor elements, the motor to ensure proper air convection and even temperature distribution within the device. As the resistive element would consume much greater power than the motor, which may be quite small, these devices would be expected to behave more akin to a constant impedance type load.

5.4.1 Electrical Characteristics

As expected the resistive appliances tested in the laboratory exhibited close to constant impedance characteristics in terms of both their active power voltage dependency and their power factor. All of the appliances tested had a voltage dependency exponent very close to that of a constant impedance load, and all consumed little to no reactive power, noting that the hair-dryer result presented here is for operation at its highest heat setting, see Table 7. The harmonic content for these loads was extremely negligible, with any content mirroring that of the supply and of the order of 2% THD.

5.4.2 Thermal Characteristics

The RC time constants and equivalent thermal resistance and capacitance of these appliances depend on the thermal mass and insulation. For example, water has a high specific heat capacity, so kettles have high thermal capacitance due to the mass and properties of the water whereas ovens have much lower thermal capacitance but

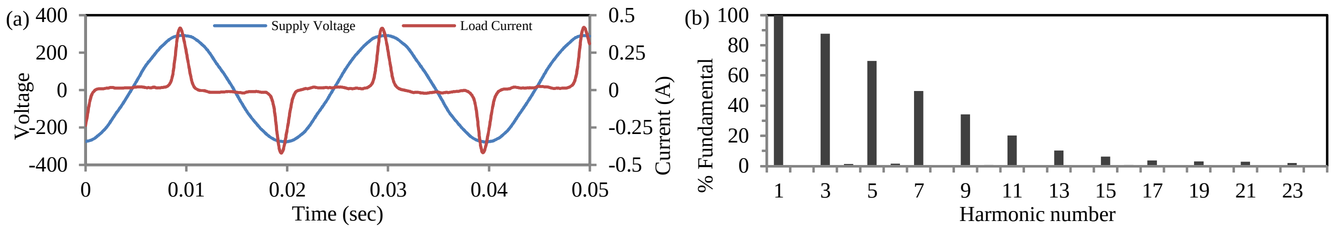

Figure 10: (a) Supply voltage and load current, and (b) Fourier Transform frequency components and magnitude for a laptop.

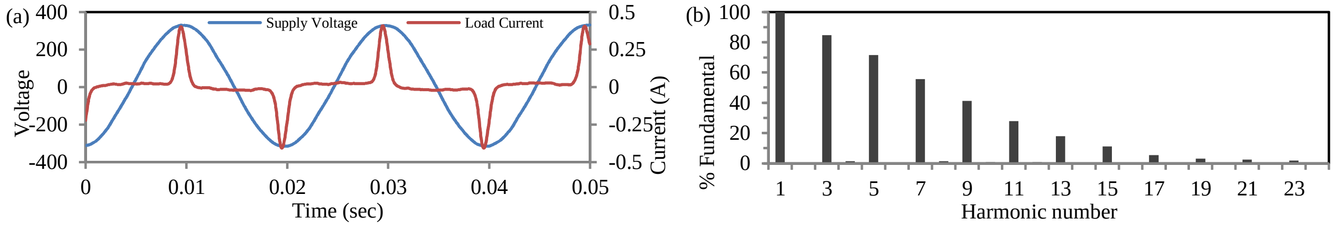

Figure 11: (a) Supply voltage and load current, and (b) Fourier Transform frequency components and magnitude for a television appliance.

Table 7: Resistive Loads Electrical Data & Voltage Dependencies.

Appliance	Power (Watt):	P.F	n_p	n_q
Resistive Space Heater	500	1	2.03	-
Oil-Filled Space Heater	2000	1	1.95	-
Hair Dryer	650	0.95	2.01	2
Iron	2000	1	2	-
Kettle	2500	1	1.95	-

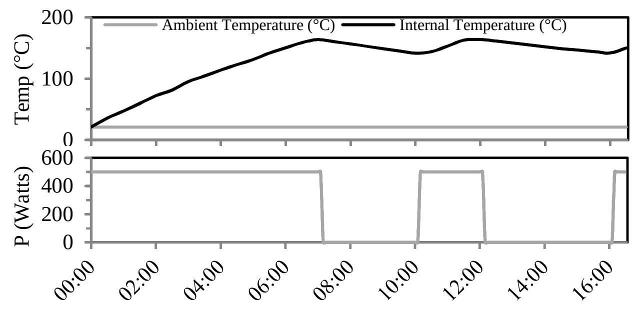

Figure 12: Active power (P) and temperature evolution of a domestic oven.

much better insulation so higher thermal resistance, see Table 8. These properties vary between different manufacturers of the same appliances and between appliance categories. Whilst some appliances may have similar time constants, the ratio of the thermal resistance to thermal capacitance determine the on-off times, so appliances with the same time constants can behave quite differently. The control of these appliances can vary, to reaching a temperature set-point, such as a kettle, to temperature regulation, such as an oven, see Figure 12. The results in Table 8 are from digital meters using thermocouples to monitor ambient and internal temperature of devices whose electricity consumption is a function of internal temperature. For plug-in devices active power was logged using an electrical three-pin plug monitor. For hard-wired devices, such as ovens, it was noted when the heat element was activated, and the power rating was assumed based on nameplate electrical data and by using a current-clamp multi-meter.

For appliances which are less accessible, a bottom-up approach estimation of the thermal characteristics can be taken, see equations (18, 19, 20), using assumptions on the device properties and materials. However, for some devices this may be quite technically challenging, particularly when calculating thermal resistances, which may be a function of a whole host of different materials, internal and external to the appliance itself. In Table 7, both storage heaters and immersion heater RC data were calculated using available data. In [31], the authors used multiple thermocouples to monitor the internal temperature of a night electric storage heater at different points within the device. The temperature data and hours of operation are used to estimate the thermal parameters for that device.

For immersion heaters, data in [32] gives warm up times for a 120 litre and a 40 litre immersion heater, going from cold to fully heated, which we take as an assumed temperature of 60 °C. Time to cool down for a large water heater is taken from detailed electrical consumption data high-resolution water heater electrical consumption

Table 8: Resistive Loads RC Data.

Appliance:	RC (hours)	R_{th} (℃/kW)	C_{th} (kWh/℃)	Rating (kW)
Kettle 1	0.87	693.35	0.00125	2.93
Kettle 2	1.48	645.78	0.00229	2.49
Oven 1	0.66	1581.62	0.00041	0.50
Oven 2	0.75	1992.08	0.00038	0.50
Iron	0.20	1736.37	0.00011	2.18
Space Heater	3.53	13.63	0.25881	1.26
Storage Heater*	32.40	810	0.04000	2.4
Immersion Heater*	43.18	254	0.17000	3.5

*Calculated with data from [31, 32, 33, 34]

data [33], with an assumed thermostatic dead-band of approximately 6 °C [34].

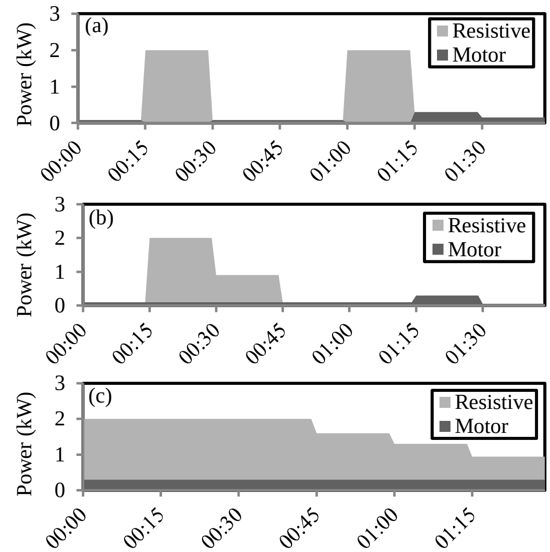

Figure 13: Wet Appliance Demand Profiles, [35], with resistive and motor demand for (a) Washing Machine (b) Dish Washer and (c) Tumble Dryers.

5.5 Wet Appliances

The electrical and thermal characteristics of wet appliances are difficult to quantify as they are a combination of power electronic interfaces for the consumer, resistive elements to heat hot water or air, and motors to rotate the appliance's drum, distribute water evenly or to circulate hot air. Depending on what stage of the operational cycle these appliances are in will result in different electrical and thermal characteristics. The assumptions made in this section are based on a review of domestic European appliances [35], and the provided demand profiles. Primarily these devices are made up of large resistive heating elements, which when on, would mean these devices are closer to constant impedance.

Furthermore, the temperature of these devices is of crucial importance in the cleaning process, so these appliances are usually equipped with temperature sensors to limit operation once a set-point has been reached. In [12] the wet appliance profile data from [35] is broken down into its constituent components, being resistive, the different motor types and power electronics. Here the basic demand is broken down into two basic categories, resistive and motor load, neglecting power electronic load component due to its very low energy requirements

The dish washer cycle, Figure 13, can be broken down into five main stages. The first uses a pump to fill the lower tank with the required water for washing. This water is then heated up using a high power resistive element. In the third step a small motor sprays this water on the dishes and utensils. The fourth and final step involves re-heating the water to a high temperature to give the kitchenware some thermal inertia to self-dry, and pumping out the used water. According to [35] the average amount of water used is 20 litres with an average temperature setting of approx 60 °C, and accordingly takes approximately 15 minutes to heat up. Using this data and

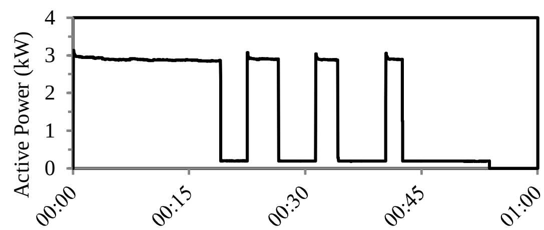

Figure 14: Active power consumption for a clothes dryer [33]

temperature decay rates similar to other devices, such as a well insulated electric kettle or small domestic water heater, RC constants can be estimated for the heating stages of the dishwasher cycle, see Table 9.

The washing machine has similar cycle structure, see Figure 13, to that of a dish washer, the main difference being that there is not a second heating cycle for hot water. Instead, cold water is used to rinse the clothes towards the end of the cycle. The average European washing machine uses approximately 66 litres of water per cycle, of which only 1/3 to 1/4 is heated at cycle initiation, and to an average temperature of 40 °C [35]. Temperature sensors are used to control the water heating process, signalling to the resistive element when the desired temperature has been reached [36, 37]. Using average European data and an assumed temperature decay rate the RC constant for heating process of a washing machine was calculated, see Table 9.

The tumble dryer, or clothes dryer, has a simpler mode of operation, and is comprised of a fan, a motor to rotate the main drum and a resistive element to heat the circulated air. The resistive element is operated thermostatically, and with a temperature set-point depending on both the user setting and the model itself, but in the range of 60 °C - 90 °C [38, 39]. The duration of operation can either be based on the humidity content of the out-going air or by a set-time dial depending on the sophistication of the model. The appliance uses less energy the further it is into the cycle, as the clothes load becomes lighter and there is less moisture content, see Figure 13. Figure 14 shows real clothes dryer data from a study on high-resolution appliance power profiles. Using an assumed set-point temperature of 65 °C and a dead-band of 5 °C, [39], this data is used to estimate a range of RC constants across the device operation.

Table 9: Wet Appliance Heating Operation RC Constants.

Appliance:	RC (hours)	R_{th} (°C/kW)	C_{th} (kWh/°C)	Rating (kW)
Dish Washer (Heating)	0.61	70.64	0.0088	2
Washing Machine (Heating)	0.65	42.77	0.0151	2
Tumble Dryer	0.70	46.50	0.015	2.95

6 Conclusions

This paper has presented the electrical and thermal characteristics of real domestic appliances based on load monitoring techniques and presented methodologies for their extraction. Household appliances can broadly be disaggregated into five appliance categories; lighting, motors, power electronics, resistive and wet appliances. Using the outlined methodology the electrical voltage dependencies and thermal RC parameters for a range of commonly used domestic appliances have been extracted from load monitoring data. Different methodological approaches for extracting thermal characteristics were used, based on data availability. Load monitoring studies are increasingly important in an ever changing load landscape and must continue to be updated for power system studies.

7 Acknowledgements

The authors would like to thank Cathal O'Loughlin for his assistance in the laboratory load monitoring that was conducted in this report.

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