Northern Powergrid

IMPACT OF VOLTAGE AND HARMONIC VARIATIONS ON DOMESTIC LOSSES

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CONFIDENTIAL

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EXECUTIVE SUMMARY

Optimal energy efficiency is a fundamental feature of any power system, as it has a direct effect on other major parameters such as cost and environmental impact. Classically, in electrical power systems, loss studies have primarily focussed on higher voltage areas of the distribution network such as generation, transmission and distribution – neglecting the residential power network (customer's side of the meter; post-distribution). However, a new focus of attention on losses within customer networks is indicated by the IET's decision to address energy efficiency measures, potentially based upon IEC 60364-8-1 *"Low-voltage electrical installations – Part 8-1: Energy efficiency*", within the yet to be published 18th Edition of the IET Wiring Regulations (BS 7671).

This report summarises the findings of the residential losses enquiry undertaken by WSP for Northern Powergrid. Losses in domestic networks and their sensitivity to voltage variations and greater levels of harmonic voltage distortion have been considered, including consideration of future domestic loading scenarios.

The overall efficiency of the domestic system has been found to be dominated by the efficiencies of appliances since losses within the residential wiring network are small. Opting for an A++ rated appliance instead of an A rated appliance could reduce annual consumption by between 3.65% and 1.16% of the average (4192kWh). This is greater than the losses in the residential wiring network which were estimated, using a model based on a typical house, to be approximately 0.2% of the energy consumed.

The impact on domestic efficiency of operating over a wider range of voltages has been considered in terms of the sensitivity of losses in the residential wiring and if the operation and efficiency of appliances would be affected. ZIP characteristics of different domestic appliance types were considered in order to determine their dependence on system voltage, and how changes to supply voltages might impact their efficiency. It is concluded that the efficiencies of most appliances are not affected by variations in voltage partly because they are dominated by non-electrical factors such as insulation and mechanical parameters and partly because many appliances utilise power electronic interfaces to control internal voltages. However, it should be noted that EA Technology's experimental results[32] have shown variations in the sensitivity of appliances to supply voltage magnitude. They found the sensitivity was not consistent for all appliances of the same type (i.e. refrigerators), but depended on the manufacturer and appliance efficiency classification. Losses in domestic wiring networks have been found to be insensitive to voltage variations despite some appliances drawing more current, and others drawing less current, when the supply voltage is reduced.

More Heat Pumps, Electric Vehicles and LV PV generation are expected in the future as part of the transition to a low carbon future. The contribution of these devices to the overall domestic efficiency is not expected to be sensitive to voltage and harmonic variations since they mainly employ electronic interfaces and the associated wiring losses are small because they are connected to the consumer panel via short connections.

Even if voltage variations altered overall domestic efficiency, some households would not be affected because they would not experience voltages at the extremes of the permitted range due to the inherent variation of voltages associated with distribution network impedances and power flows. Also, it should be noted that the effects of voltage variations on domestic systems would only be realised for part of the year due to daily and annual variations in circuit loading and corresponding system voltages.

The ENA's proposal to include the consideration of harmonics up to the 100th harmonic in a future revision of Engineering Recommendation G5/4-1 "Planning Levels for Harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the United Kingdom"[1]; suggests that the influence of harmonics within the power system are of growing concern, possibly due to a predicted growth in power electronic devices domestically. Greater levels of harmonic distortion are likely to increase harmonic losses in domestic wiring networks, however, it is speculated that the increase is mainly attributed to customer devices rather than the impact of the distribution network. Increases in the number of electronic devices in homes could mean that their harmonic currents will be the main source of harmonic currents within a domestic network. Although equipment's harmonic currents are limited by BS EN 61000-3-2:2014 *"Electromagnetic compatibility (EMC) Limits: Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)"*, it is estimated that the aggregated harmonic current due to all electronic devices in a home will be greater than the harmonic currents flowing in constant impedance devices due to the effect of background harmonic voltage distortion.

In the near future, the UK looks to relinquish its EU membership – leaving any EU energy regulations with it. Domestic appliances connected within the UK energy network may no longer have to follow the stringent, but efficiency-boosting, EU rules regarding their operation. As such, potential exists for poorly-regulated appliances to become common within UK domestic networks, having detrimental effects on the electrical efficiency of UK homes. The impact on domestic efficiencies of using these less efficient appliances would be significantly greater than the effect of varying supply voltages or harmonic levels.

[1] http://www.dcode.org.uk/assets/uploads/ENA_ER_G5_Issue_4_Amendment_1__2005_.pdf

1 INTRODUCTION

Northern Powergrid commissioned WSP to undertake an inquiry into losses in domestic customer networks.

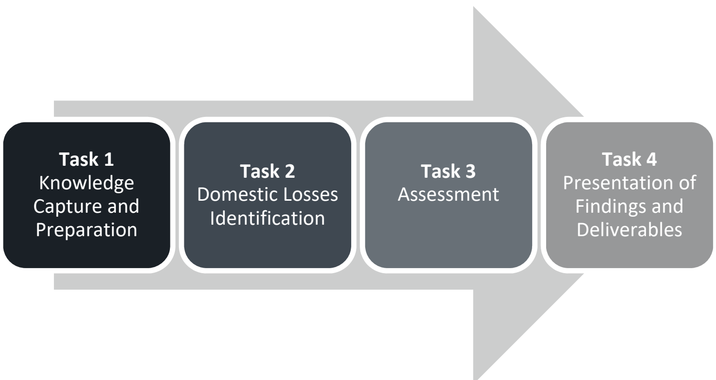
In particular, the objective of the work was to explore how the losses in domestic customers' networks are affected by variations in supply voltage and harmonic voltage levels; specifically customers' energy absorption and the behaviour of their networks. Concentrating on the situation today, whilst extrapolating to the future load composition, the aim was to gather information in order to assess the impact of voltage reduction and variations in harmonic levels on consumers' losses.

This is a very important aspect to be considered as voltage and harmonic levels are expected to change as a result of changes in domestic network usage. The connection of more distributed generation means that system voltages can be increased, particularly at times when export exceeds local demand. Also, recent DNO projects have demonstrated that lowering the supply voltages can reduce demand with the advantage of providing distribution network capacity for additional loads and generation sources – successful examples include Electricity North West's CLASS[2], Western Power Distribution's Equilibrium[3] and Scottish Power Energy Networks Flexible Networks projects as described in Section 2.1. Harmonic levels in distribution networks are changing as a result of an increase in the number of power electronic devices being connected on the domestic network.

1.1 SCOPE OF WORK

The scope of work has been divided into four tasks as shown in Figure 1.

Figure 1 - Study tasks



[2] http://www.enwl.co.uk/class#
[3] https://www.westernpowerinnovation.co.uk/Projects/Network-Equilibrium.aspx

High level descriptions of the tasks are:

- Task 1 – Literature review to identify the potential extent of voltage and harmonic variations that need to be considered in the inquiry
- Task 2 – A review of what is already known about losses on the customer's side of the meter and their sensitivity to voltage and harmonic variations
- Task 3 – Assessment of the impact of the variation of voltage and harmonics on domestic customer losses
- Task 4 - Presentation of Findings and Deliverables

The project concentrates on the impact on domestic system losses and efficiency of distribution network operation in terms of voltage variations and harmonic distortion levels. The impact on distribution network losses of different operational approaches is not considered.

2 TASK 1 - VOLTAGE AND HARMONIC VARIATIONS

2.1 VOLTAGE VARIATIONS

Variable losses, i.e. copper losses, depend upon network currents which in turn depend upon the power requirement of the connected demand and the export from generators. In some cases power demand depends on voltage, so changes in voltage alters current flows and losses as a consequence, hence the extent of potential variations in voltage impacts losses.

GB distribution network operators are required to maintain LV supply voltages within +10%/-6% of 230V/400V nominal in accordance with the ESQCR[4]. This means that supply point voltages can vary between the maximum of 253V and the minimum of 216.2V. The present control of LV supply voltages is mostly passive and they vary according to variations in the voltage in the upstream system and the voltage drop/rise in the local transformer (HV/LV) and both HV and LV circuits. A customer's supply voltage therefore depends upon where they are connected along the circuit and the power flow in the circuit which tends to vary with the time of day and time of year. Only customers connected at the end of circuits tend to experience voltages near the extremes of the permitted range. However, network changes that are already happening and future changes mean that LV supply voltages are likely to follow a different profile and may ultimately be of different magnitudes.

British Standard EN 50160 is a quality of supply standard which defines a range of acceptable parameters regarding the delivery of electrical power for domestic applications. For instance, it allows for a variation in supply voltage of ±10% of the nominal value for a long period of time[5]. This wider voltage range is the standard which is applied to the rest of Europe, indicating that the UK could conceivably decrease its lower voltage boundary from -6% to -10% as long as this does not have adverse impact on network users[6].

An ENA Task Group has reviewed the current lower bound of the statutory voltage limits at LV customers' terminals, in particular changing the current lower to -10%. Advantages and disadvantages of the change are presented in the ETR 140 which recommended the subsequent consultation which is now closed, but yet to be reported back.

Voltages are increasingly likely to operate at the extremes of the limits more often due to the increasing incorporation of low carbon technologies within the distribution network, as well as the transition from passive network control to more active network control. For instance, in the case where significant amounts of domestic

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[4] http://www.legislation.gov.uk/uksi/2002/2665/contents/made
[5] H. Markiewicz and A. Klajn, "Standard EN 50160 - Voltage Characteristics in Public Distribution Systems," Wroclaw, 2004
[6] WPD, "Network Equilibrium - Detailed Design of the Enhanced Voltage Assessment Method," 2016. https://www.westernpower.co.uk/docs/Innovation/Current-projects/Network-Equilibrium/SDRC-1-Detailed-Design-of-the-enhanced-Voltage-Ass.aspx

solar generation is connected with the LV distribution network, resulting in periods of the day where surplus generation causes the distribution network voltage to experience a rise towards the upper limit (e.g. midday), and also periods where solar generation is lower but demand is higher (night), resulting in the distribution network voltage experiencing a decrease in comparison.

It is possible that LV supply voltages will be reduced as Electricity North West's CLASS[7] and Western Power Distribution's Equilibrium[8] projects have shown advantages in reducing voltages at the customer's side. Demand is seen to reduce along with voltage, however, these studies have not explained the mechanisms or explained why demand is reduced. Conversely, the connection of more generation (e.g. customer-side generation) to the distribution system means that network voltages are likely to increase especially at times when export exceeds local demand. An example of this method of operation was observed in Western Power Distribution's LV Templates Project, highlighted within ENA's ETR 140[9], which stated that while this particular was example was an isolated incident, it predicted that this could become much more commonplace in the future.

In addition, there have been suggestions that voltage limits could be extended, up and down, without detrimental effect on customer satisfaction[10]. As part of their Flexible Networks project, Scottish Power Energy Networks carried out studies on their LV distribution network, finding that no detrimental effects on performance were experienced by customers and also found that a sizeable amount of additional Distributed Generation capacity headroom was acquired; a 2% network voltage reduction lead to an additional 90% of solar PV generation (by kW)[11]. Consequently, customer's networks and their equipment could be operated at different voltage magnitudes in the future.

Based on the findings and indications discussed here, it is not beyond comprehension that voltage limit standards will be changed meaning that some LV customers may be supplied at lower voltages down to -10%, rather than the present -6% limit, with a potential impact on their losses.

2.2 HARMONIC VARIATIONS

Injected harmonic currents cause harmonic voltages in power systems, which in turn cause harmonic currents to flow in other loads, such as fixed impedance heating demands and motors. Harmonic currents flowing through a power system are known to cause losses, and because some harmonic currents are directly dependent upon the harmonic voltage levels, these losses are also sensitive to them. The extent of the overall sensitivity of losses depends upon the extent of the harmonics and also the composition of the demand and the degree to which

[7] http://www.enwl.co.uk/class#
[8] https://www.westernpowerinnovation.co.uk/Projects/Network-Equilibrium.aspx
[9] ENA, "Engineering Technical Report 140: Statutory Voltage Limits at customers' terminals in the UK and options for future application of wider limits at low voltage"
[10] http://www.enwl.co.uk/docs/default-source/class-documents/changing-standards-closedown-report.pdf?sfvrsn=8
[11] Energy Networks Association ETR 140 – July 2017

their harmonic currents vary with harmonic voltage. The effect of variations in harmonic voltage distortion on different types of appliances is explained in Section 5.4.

Engineering Recommendation G5/4-1 “Planning Levels for Harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the United Kingdom” sets planning and compatibility limits for harmonic voltage distortion in the UK for all voltage levels. Compliance is required in accordance with the Distribution Code[12] as enforced through each distribution network operator’s licence conditions[13].

G5/4-1 defines acceptable limits of individual harmonic distortion contribution for harmonics up to the 50th harmonic as a percentage of the system voltage. However, the ENA G5 Review Workgroup is developing proposals for the modification of G5/4-1 and the future issue of G5/5 which is not yet available for consultation. It is understood that the workgroup are considering extending consideration up to the 100th harmonic because of the increasing power electronic nature of appliances and loads connected to the UK power network (e.g. employment of rectifiers for provision of DC supplies – drawing harmonic currents) which draw high harmonic currents due to their very high switching frequencies[14].

Future implementation up to the 100th harmonic could be viewed as a precursor to greater ranges of harmonics being present within the distribution network - leading to changes in losses.

It is not understood that the limits for the 2nd to 50th harmonics will be changed, but this cannot be assured until the revised G5 Engineering Recommendation is issued.

[12] http://www.dcode.org.uk/assets/uploads/DCode_v28_May_2017__020517_final.pdf
[13] https://epr.ofgem.gov.uk/Content/Documents/Electricity%20Distribution%20Consolidated%20Standard%20Licence%20Conditions%20-%20Current%20Version.pdf
[14] “Engineering Recommendation G5/5 Harmonic Voltage Distortion and the Connection of Non-Linear and Resonant Plant and Equipment to Transmission Systems and Distribution Networks in the United Kingdom” – Energy Networks Association

2.3 TASK 1 CONCLUSIONS

Task 1 - Conclusions
Voltages apparent in distribution networks and experienced by customers are likely to change as the way that the distribution network is operated evolves and due to the impact of new connections of low carbon technologies. More customers could experience operation at the permitted extremes of the voltage range, customers may experience voltages near these limits more frequently and therefore there could be greater variation in a customer's voltage. Although voltage limits may not be changed, it is possible that the lower LV voltage tolerance could be reduced from -6% to -10% meaning that the variability of customers' voltages could increase. Distribution network harmonic distortion is expected to increase with the connection of more non-linear power electronic devices. This is reflected by the proposal that Engineering Recommendation G5 should include consideration of harmonics up to the 100th order. Although there is no indication that the existing limits for harmonics up to the 50th order will change in the short term, the harmonic levels within the distribution network could increase within the existing permitted range.

3 TASK 2A - LITERATURE REVIEW

A literature search has been carried out in order to determine if any prior work had been undertaken regarding losses on the customer's side of the meter.

3.1 PREVIOUS WORK ON DOMESTIC LOSSES

To date, the overwhelming majority of losses studies that have focussed on the transmission and distribution electricity network. With precedence being placed so heavily on these areas, little to no research has been found regarding the properties of losses in domestic networks; customers' homes.

3.2 IEC 60364-8-1 LV ELECTRICAL INSTALLATIONS

The International Electrotechnical Commission (IEC) has developed a standard (IEC 60364-8-1:2014 – "Low-voltage electrical installations - Part 8-1: Energy efficiency") which concerns the optimal installation of low voltage electrical wiring in terms of electrical efficiency. The IET has indicated that energy efficiency measures, potentially based upon IEC 60364-8-1, will be included in the yet to be published 18th Edition of the IET Wiring Regulations (BS 7671)[16]. The development of this IEC and introduction within the Wiring Regulations shows a new focus of attention on losses within customer networks.

IEC 60364-8-1 provides recommendations regarding the design and installation of low voltage networks within buildings or systems, in order to attain the most effective electrical system in terms of optimising losses[15]. Although the standard mentions residential and small building installations, the applicable requirements are very limited compared to larger installations, specifically medium buildings, large buildings and industrial and infrastructure installations.

IEC 60364-8-1 requires attention to the following three parameters in order to manage energy losses[16]:

- **Maximum voltage drop**: for a constant impedance power device a reduction in system voltage would require an increase in the current being supplied to a particular appliance in order to ensure correct operation – thereby increasing I^2R losses within the electrical wiring – in the case of constant power devices, where a drop in voltage would be compensated by an increase in current drawn in order to compensate.

- **Conductor sizing**: the resistance of a conductor is inversely proportional to its Cross Sectional Area (CSA) – therefore increasing CSA reduces resistance. However, as more copper is required to produce

[15] International Electrotechnical Commission, "Low-voltage electrical installations - Part 8-1: Energy efficiency," Geneva, 2014
[16] Schneider Electric, "IEC 60364-8-1: Setting a New Standard for Efficient Buildings," 2015.

larger conductors, a trade-off should be found where the cost of the conductor is justified by the reduction in I^2R losses.

- **Consumer unit placement**: reducing the length of conductor from voltage source (in buildings this is the consumer unit) to load (socket) reduces the voltage drop and conductor resistance.

Additionally, IEC 60364-8-1 considers voltage measurement and harmonic measurement within installations, with the same view of optimising efficiency[15].

3.3 CAUSES OF LOSSES IN THE DOMESTIC NETWORK

Losses within customers wiring are a source of inefficiency and electrical losses within the domestic network, but so are electrical appliances themselves. Energy is dissipated in non-useful ways not associated with the principle function of the device, such as heat from a lightbulb. The European Commission has produced a means of categorising the energy efficiency of typical household appliances by comparing their specific annual energy consumption against a 'standard' equivalent model in their appliance category, then giving them a rating ranging from A (most efficient) to G (least efficient) – the *Energy Efficiency Index (EEI)*[17]. In some cases, depending on appliance, the scale can increase to A+++.

The Energy Efficiency Index is categorised as the ratio between the appliance's annual energy consumption and the 'standard' appliance's energy consumption:

$$EEI = \frac{AE_C}{SAE_C} \times 100$$

The Annual Energy Consumption, AE_C, is calculated differently depending on the appliance type, due to the fact that each appliance type uses energy in different ways and for different periods of time during their average 'cycle'. In the case of a dishwasher, for example, the AE_C considers:

- The energy consumed in a standard cycle (kWh)
- The power consumed in the device's 'left-on' mode during a standard cycle (W)
- The power consumed in the device's 'off' mode during a standard cycle (W)
- The time taken for a standard cycle to be completed (minutes)
- The total number of standard cleaning cycles per year – for the dishwasher, said to be 280.

[17] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010R1059&from=EN

The Standard Annual Energy Consumption, SAE_C, represents the annual energy consumption of the 'standard' appliance – chosen as a reference for which all other appliances within its category are compared against, in order to classify their levels of efficiency.

The EEI classification thresholds are outlined for a number of different appliances in Table 1 [17] [18] [19] [20] [21]:

Table 1 – EEI classes of domestic appliances

Energy Efficiency Index (EEI)					
Energy Efficiency Class	**Dishwasher**	**Refrigerator**	**Washing Machine**	**Ovens**	**Tumble Dryers**
A+++	EEI < 50	EEI < 22	EEI < 46	EEI < 45	EEI < 24
A++	50 ≤ EEI < 56	22 ≤ EEI < 33	46 ≤ EEI < 52	45 ≤ EEI < 62	24 ≤ EEI < 32
A+	56 ≤ EEI < 63	33 ≤ EEI < 42	52 ≤ EEI < 59	62 ≤ EEI < 82	32 ≤ EEI < 42
A	63 ≤ EEI < 71	42 ≤ EEI < 55	59 ≤ EEI < 68	82 ≤ EEI < 107	42 ≤ EEI < 65
B	71 ≤ EEI < 80	55 ≤ EEI < 75	68 ≤ EEI < 77	107 ≤ EEI < 132	65 ≤ EEI < 76
C	80 ≤ EEI < 90	75 ≤ EEI < 95	77 ≤ EEI < 87	132 ≤ EEI < 159	76 ≤ EEI < 85
D	EEI ≥ 90 (least efficient)	95 ≤ EEI < 110	EEI ≤ 87 (least efficient)	EEI ≥ 159 (least efficient)	EEI ≥ 85 (least efficient)
E	-	110 ≤ EEI < 125	-	-	-
F	-	125 ≤ EEI < 150	-	-	-
G	-	EEI ≥ 150 (least efficient)	-	-	-

If an appliance has an EEI of 100, then it is of equal efficiency to the standard model that all other appliances of this type are compared against. All dishwashers rated D and above consume less energy than the standard dishwasher. The difference in efficiency between an 'A' rated dishwasher and an 'A++' rated dishwasher can be up to 21% of the consumption of the standard machine when considering the most efficient A++ rated appliance and the least efficient A rated dishwasher.

Taking the midpoint EEI values it is apparent that changing from an 'A' (EEI= 63+71 /2 = 67%) rated dishwasher to 'A++' (EEI= 50+56 /2 = 53%) corresponds to a saving of 65kWh (14% of the 462kWh annual consumption for the standard 12 setting dishwasher). 65kWh corresponds to an annual saving of approximately 1.6% of the annual consumption of a household with an assumed annual consumption of 4192kWh[22]. Similar significant savings of typical domestic energy consumption can be achieved by changing other appliances from A to A++ rated as shown in Table 2.

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[18] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010R1060&from=EN
[19] http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32010R1061&from=EN
[20] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2014:029:0001:0032:EN:PDF
[21] http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32012R0392&from=EN
[22] http://www.networkrevolution.co.uk/wp-content/uploads/2015/01/CLNR-L094-Insight-Report-Enhanced-Domestic-Monitoring.pdf

The annual energy saving by choosing an appliance of one class better can produce a significant reduction in the overall annual consumption and therefore the household electrical efficiency. Based on an assessment of typically sized appliances, a total saving of more than 400kWh could be achieved by switching an A rated dishwasher, refrigerator, washing machine, oven and tumble dryer for A++ rated appliances.

The thought process taken by the average consumer could dictate that by purchasing an 'A' rated appliance, they believe that they are being energy efficient on the basis that there are several lower classifications. However, the extent of the further energy efficiency that could be achieved by purchasing a higher rated appliance is perhaps not apparent to all consumers. From this it is concluded that the overall energy efficiency of domestic network electrical consumption is very much influenced by a customer's choice in the appliances they purchase, install and operate.

Table 2 – Energy savings delivered when swapping from A to A++ rated appliances [17] [18] [19] [20] [21]

Appliance Type	A class EEI	A++ class EEI	Improved efficiency as percentage of standard appliance	Standard Appliance Annual Consumption	Reduction in annual energy by choosing A++ instead of A	Reduction in annual energy as % of 4192kWh
Dishwasher (12 place settings)	67%	53%	14%	462kWh	65kWh	**1.54%**
Refrigerator (150 litres)	48.5%	27.5%	21%	330kWh	69kWh	**1.65%**
Washing machine (6kg)	63.5%	49%	14.5%	334kWh	48kWh	**1.16%**
Oven (60 litres)	94.5%	53.5%	41%	241kWh*	99kWh	**2.36%**
Tumble Dryer	53.5%	28%	25.5%	600kWh**	153kWh	**3.65%**

*On the basis of using a 2kW oven for 20 minutes each day (2000W x 0.33 x 365 = 241kWh)

**On the basis of 160 cycles each consuming 3.75kWh

3.4 TASK 2 CONCLUSIONS

Task 2 - Conclusions
Inefficiencies in residential electrical energy consumption arise from losses in wiring, but also due to energy not experienced in the principal function of appliances, i.e. the heat associated with lighting. Although losses in electrical transmission and distribution systems have been investigated by many, there is very little information available about losses within residential wiring. However, more future interest may be indicated by the new standard IEC 60365-8-1 concerning the efficiency of low voltage electrical wiring and future inclusion of similar considerations in the IET Wiring Regulations. Significant energy savings and improvements in overall domestic efficiency can be achieved by switching to appliances with higher classifications.

4 TASK 2B - MODELLING OF LOSSES IN DOMESTIC WIRING NETWORK

In the absence of previous analysis of losses in domestic wiring networks, an Excel model was produced to estimate the (I^2R) losses within a domestic wiring networks by simulating a day using a typical load profile and assuming a typical cabling layout.

The tool analyses current flow within the wiring network over the period of a day, and was designed such that all parameters could be customised freely, to allow the modelling of wiring networks of different sizes and of varying load profiles.

4.1 DESIGN OF MODEL

WIRING NETWORK

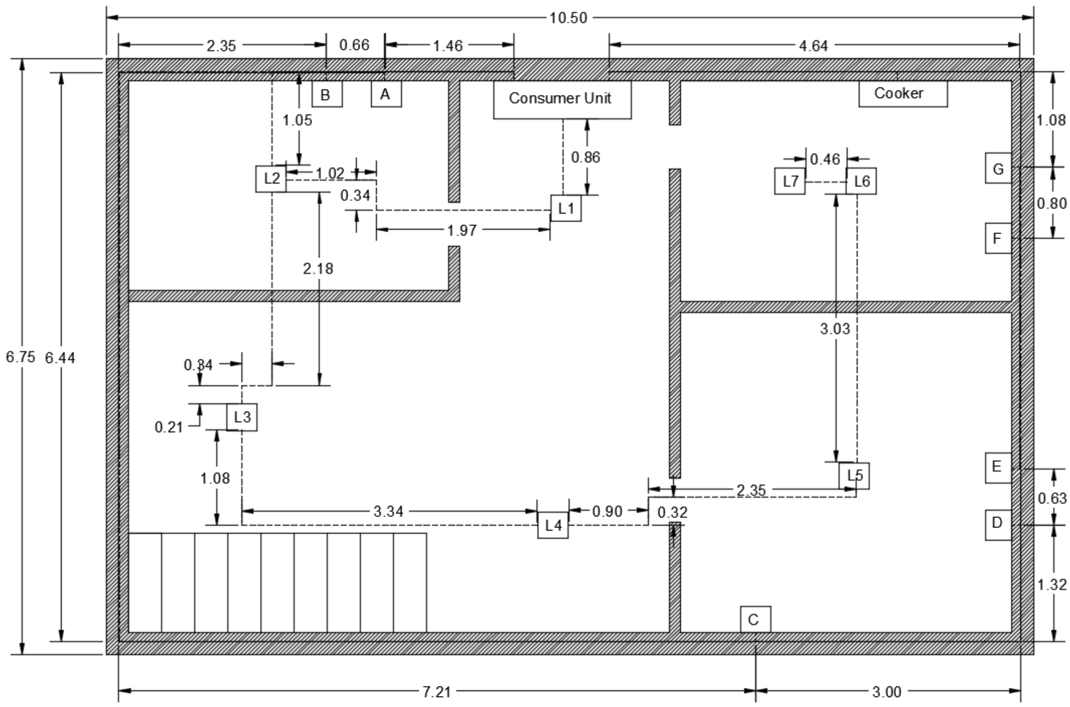
A typical domestic wiring network was assumed, consisting of multiple circuits, within the layout of a home as illustrated in Figure 2 and Figure 3. Upstairs and downstairs socket ring and radial lighting circuits were assumed in addition to dedicated cooker and shower circuits – the block diagrams in Figure 4 and Figure 5 illustrate the fundamental operation of ring (downstairs/upstairs sockets) and radial (downstairs/upstairs lighting) circuits.

CABLE SIZES

The assumed lengths of the segments of the circuits are given in Table 3 in accordance with the wiring layouts shown in Figure 2 and Figure 3. Typical cable sizes were assumed; 25 mm^2 for the tails from the meter to the consumer unit, 2.5 mm^2 for all socket circuits, 1.5 mm^2 for all lighting circuits and the cooker and shower circuit cables were taken to be 6 mm^2.

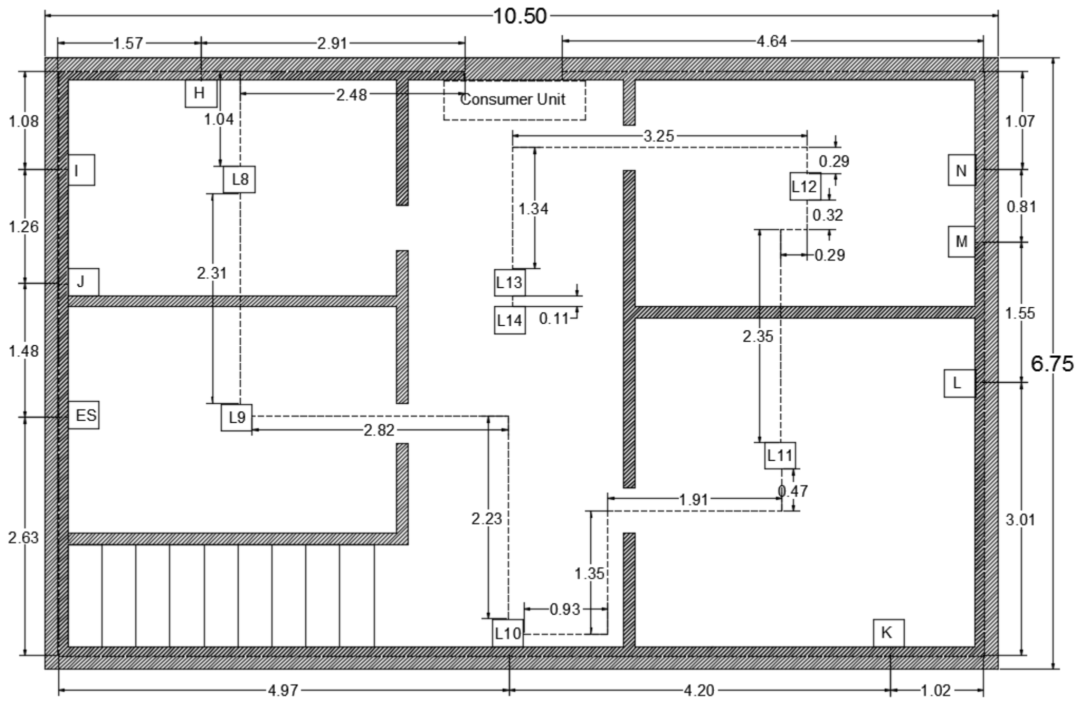
The current ratings of these cable types based on typical installation conditions were checked to be adequate for the maximum possible current flow required to supply its maximum demand.

Figure 2 – Ground floor plan (all lengths in metres)



Downstairs Plan

Figure 3 – First floor plan all lengths in metres



Upstairs Plan

Figure 4 – Downstairs socket (ring) circuit (CU = consumer unit)

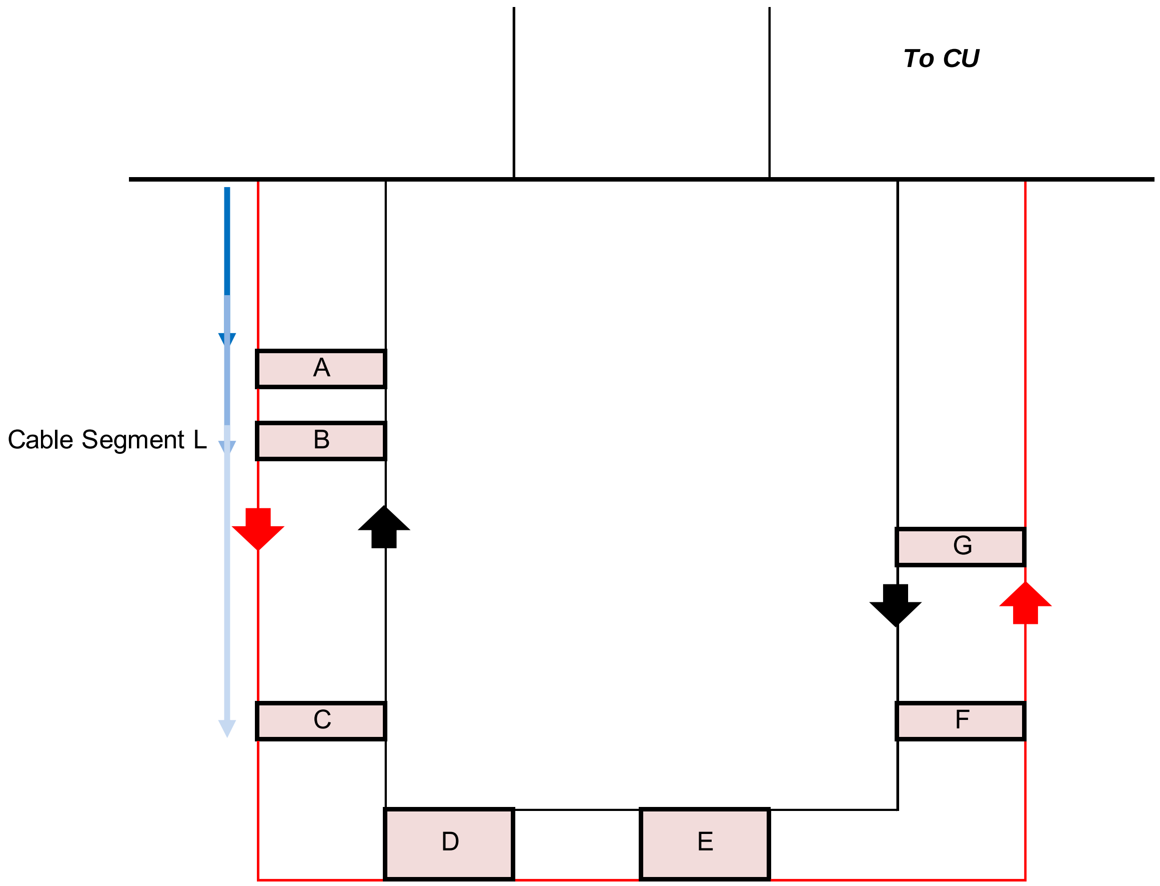
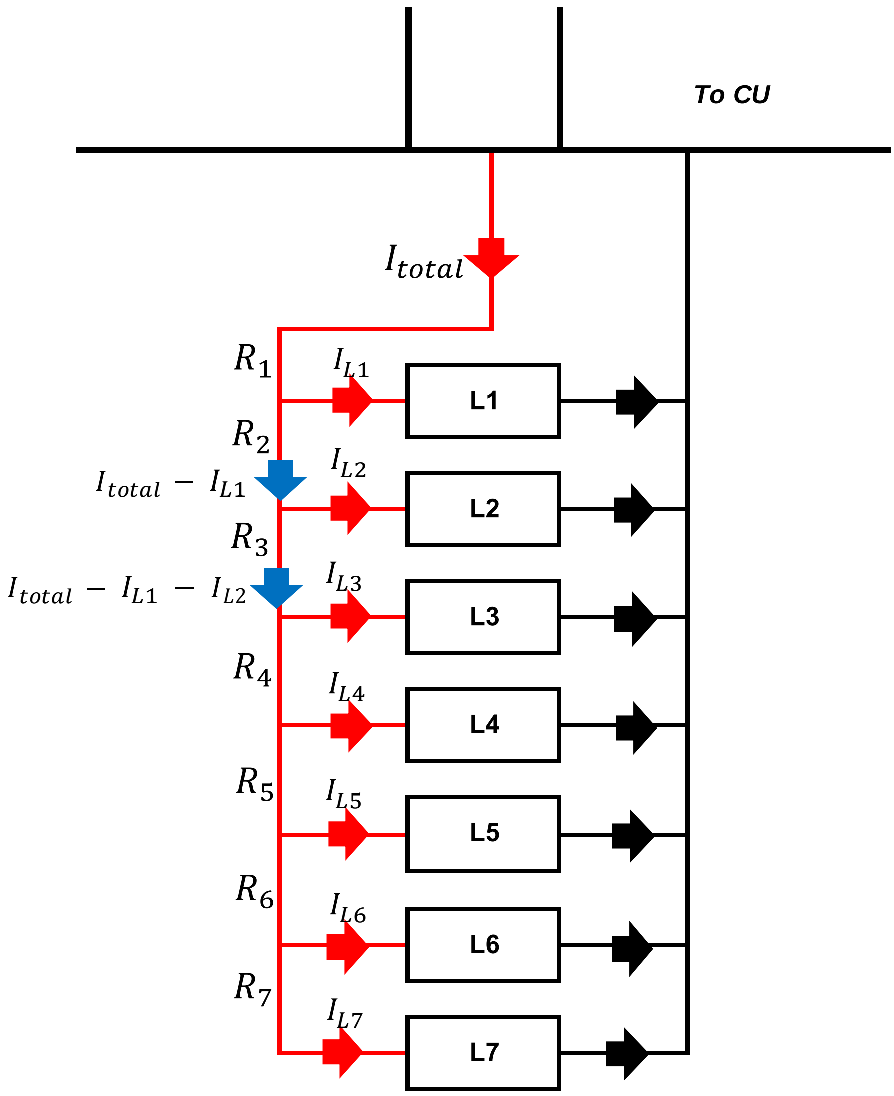


Figure 5 – Radial downstairs lighting circuit



$$I_{total} = \sum_{i=1}^{N} I_{L_i}$$

Table 3 – Domestic wiring parameters

	Socket	CSA (mm^2)	Cable Segment L (m)	Resistance [Total for Ring Circuits] (Ω)
Downstairs Sockets	A	2.50	1.46	0.216
	B		0.66	
	C		16.00	
	D		4.32	
	E		0.63	
	F		2.62	
	G		0.80	
Upstairs Sockets	H	2.50	5.41	0.250
	I		2.65	
	J		1.26	
	K		13.28	
	L		4.03	
	M		1.55	
	N		0.81	
Cooker	Cooker	6.00	28.97	0.081
Electric Shower	Shower	6.00	8.30	0.023
Downstairs Lighting	L1	1.50	0.86	0.010
	L2		3.33	0.037
	L3		2.73	0.031
	L4		4.42	0.050
	L5		3.57	0.040
	L6		3.03	0.034
	L7		0.46	0.005
Upstairs Lighting	L8	1.50	6.02	0.067
	L9		2.31	0.026
	L10		5.05	0.057
	L11		4.66	0.052
	L12		2.96	0.033
	L13		4.88	0.055
	L14		0.11	0.001
Tails	-	1.00	1.00	0.00067

LOSS CALCULATION

The I^2R losses associated with transferring power from the consumer unit to the appliance(s) were determined based on the resistance of the sections of cable in the network, as listed in Table 3, allowing for both live and neutral conductors. Conductor resistance was determined based upon their length and cross-sectional area, using the known resistivity of copper.

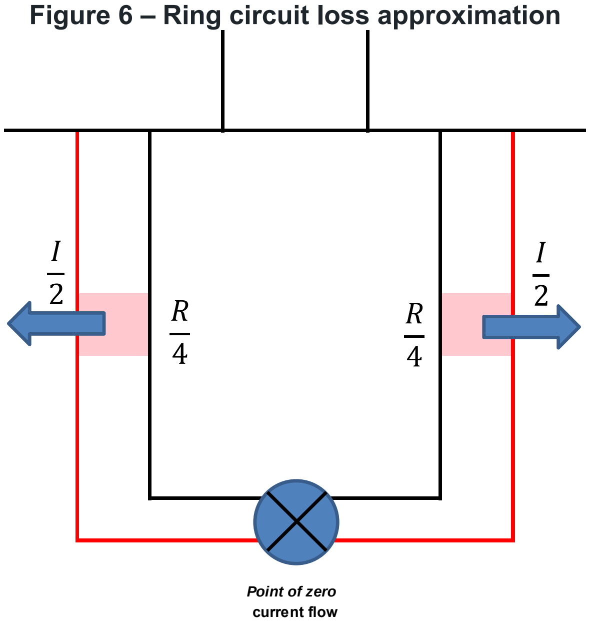
$$R_{cond.} = \frac{\rho L}{A} \qquad (1)$$

The methodology behind calculating these losses depended on the type of circuit in question; ring or radial.

RING CIRCUIT

Due to the complexity of the ring circuit, an approximation has been used to determine the I^2R losses incurred within its wiring. The system shown in Figure 4, has been simplified as shown in Figure 6; specifically by placing two lumps of half the total current, each a quarter of the total ring resistance away from the consumer unit. Losses are calculated using allowing for the flow of the current through the phase and neutral conductors.

Figure 6 – Ring circuit loss approximation



$$P_{Loss} = 2\left[2 \times \left(\frac{I}{2}\right)^2 \left(\frac{R}{4}\right)\right] \qquad (2)$$

Where:

- *I* is the sum of the current flow in the loop at a given time interval
- *R* is the resistance of the conductor loop

This approximation is applied to both the *Downstairs Sockets* and *Upstairs Sockets* ring circuits.

RADIAL CIRCUIT

Domestic lighting circuits in residential properties typically use a radial topology, as illustrated in Figure 5. The current required to effectively serve the load on the circuit at any given time is carried by the first conductor segment between the Consumer Unit and the point where the first light is connected, whilst the current flowing in the other circuit segments depends on only the current supplied to downstream lights. The I^2R losses in each segment are easily calculated by determining the current in that segment and the resistance of the segment.

CIRCUIT LOAD PROFILES

The aforementioned calculations are performed for each circuit individually and ultimately summed for the whole day (24 hours). An accumulative figure for both total household energy consumption and the losses in the wiring network are calculated for an assumed load profile, allowing a domestic wiring loss percentage to be determined.

Common household appliances, ranging from low power-consuming electronics to higher power appliances such as heaters or electric showers, along with different lighting technologies were considered in order to produce a realistic simulation.

Operation of each socket, light, the cooker and the shower in a typical day was developed based on typical usage cognisant of the household average daily electricity consumption (by appliance type) provided by Northern Powergrid's CLNR trial[23], but noting that this data considers only some major domestic appliances and lighting; data was not provided for all appliances.

The daily energy consumption in the modelled house is approximately 11.5 kWh, corresponding to 4192 kWh per year – the average household energy consumption according to the CLNR trial[24]. In the CLNR trial, 2170 kWh (annual consumption) were not accounted for, due to lack of data being collected for various appliances such as heaters or electric showers.

The equivalent average *annual* consumption of 4192 kWh was achieved in the model by including a 9kW shower (being used for 20 minutes per day – to simulate general use) and increasing the consumption of the other appliance profiles to compensate for the unaccounted-for energy consumption.

The re-distribution to the appliance data provided in the CLNR trial is allocated to each appliance by following their respective share, according to the original study data. The resultant profiles are shown in Figure 7.

The kW profiles are defined on the basis that the power is consumed continuously to achieve the target daily energy consumption, but, this is not how it occurs in practice; in reality power is consumed over shorter periods.

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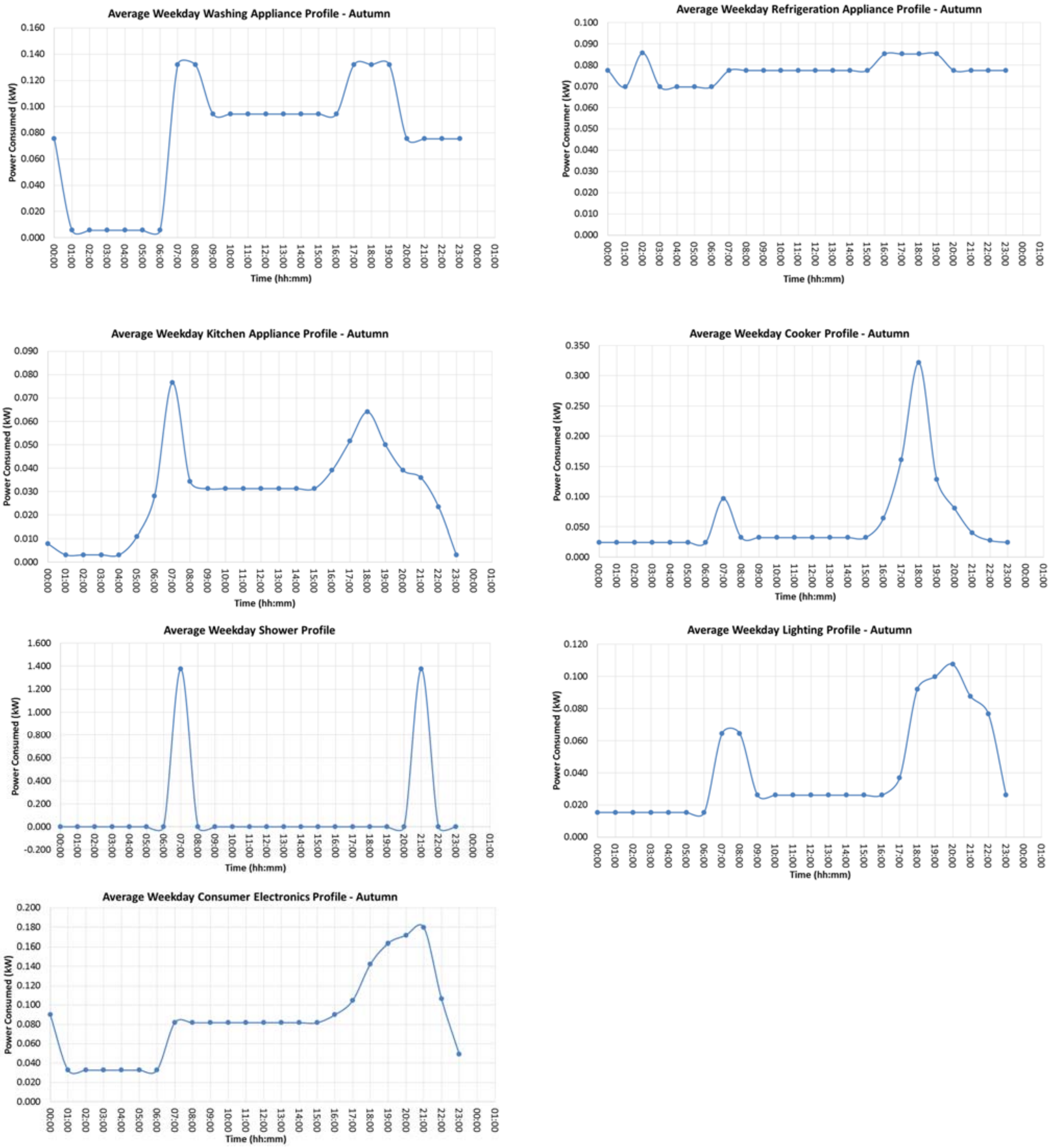
[23] http://www.networkrevolution.co.uk/project-data-download/?dl=TC2a.zip
[24] http://www.networkrevolution.co.uk/wp-content/uploads/2015/01/CLNR-L094-Insight-Report-Enhanced-Domestic-Monitoring.pdf

To simulate the more sporadic nature of energy consumption, it is assumed that the energy is consumed over 7.5 minutes per half hour. This means that the associated current is four times the value corresponding to the current if the energy was supplied over the whole half hour. The I^2R energy losses only occur for a quarter of the time (7.5 minutes) though. Assuming that the energy is consumed over 7.5 minutes is considered to be realistic and appropriate for this simple calculation on the basis that some loads will have a shorter duty cycle, such as a kettle, and others operate for longer such as a TV or oven. 7.5 minutes is considered representative of the duration of the operation of an electric shower or a refrigerator motor.

Figure 7 – Modelled circuit load profiles



4.2 RESULTS

Based on the aforementioned dimensions and load profile for the assumed domestic wiring network, the results of the calculation showed losses to be ***0.2%*** of the home's total energy consumption on the assumed typical day. Extrapolated to the whole year, the annual energy lost in the domestic wiring is 8.5kWh.

Factors which could cause this percentage to vary include length of conductor (i.e. distance from socket to consumer unit), conductor cross sectional area (affecting resistance) and the load profile for each circuit.

4.3 DOMESTIC WIRING LOSS CALCULATION CONCLUSIONS

Domestic Wiring Loss Calculation – Conclusions
Losses in the assumed domestic wiring network were calculated to be 0.2% of the supplied energy. Based on annual losses of 8.5kWh for the assumed installation and usage,, domestic wiring losses are small compared to consumption and the inefficiencies of appliances.

5 TASK 3 - EVALUATING SENSITIVITY OF LOSSES TO VOLTAGE AND HARMONIC VARIATIONS

5.1 APPROACH

The overall impact of the variation of voltage and harmonics on domestic losses and efficiency has been evaluate by following the stepped approach as shown in Figure 8.

Figure 8 – Stepped approach for evaluation of the impact of voltage variations on overall domestic network efficiency

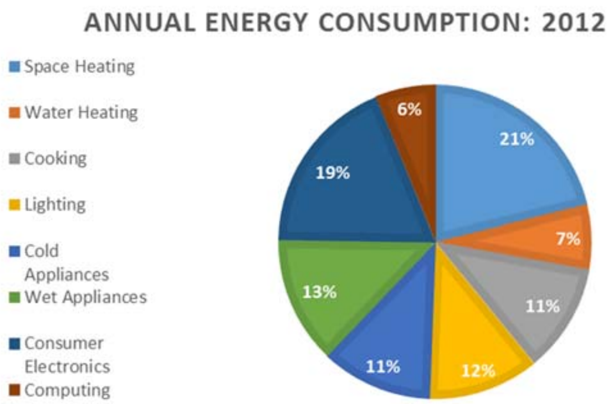
- **a** • Establish the expected composition of future domestic demands
- **b** • Establish the typical split of the annual domestic energy consumption between load types
- **c** • Establish typical efficiencies of different types of domestic appliances
- **d** • Establish how the efficiency of different types of individual appliance is affected by variations in voltage and harmonics
- **e** • Establish how the losses in domestic wiring networks change with variations in voltage and harmonics as a direct consequence and a consequence differences in the behaviour of the equipment connected to the network.
- **f** • Combine the results of the preceding points to establish the overall sensitivity of domestic losses variations in voltage and harmonic levels

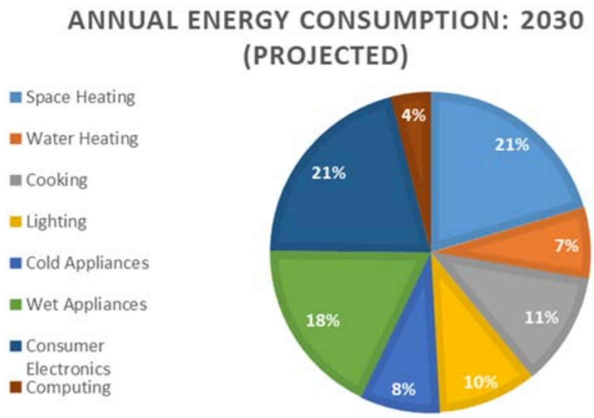
5.2 QUANTIFYING DOMESTIC APPLIANCE USAGE

EXISTING USAGE

In order to understand the domestic network's sensitivity of losses to voltage and harmonic variations by extrapolating understanding of the sensitivity of individual equipment types to the whole network, it is first vital to understand the make-up of the demand. The chart on the top of Figure 9 shows the typical split of the demand in terms of appliance type, from 2012[25]:

Figure 9 – Split of annual domestic energy consumption in UK (2012 & 2030)[25]





PROJECTED COMPOSITION OF FUTURE DOMESTIC DEMANDS

Historically, domestic demand tended to be dominated by constant impedance loads such as resistive heating elements and filament-based lighting. However, there is a growing trend for domestic networks to include more constant power and current devices – stemming from the adoption of low energy alternatives and proliferation of consumer electronics, such as new lighting technologies, power supplies and electronically-controlled appliances including refrigerators and washing machines.

In order to identify the effects of future wider voltage and harmonic variations on domestic customer losses, it is important to consider the way in which domestic composition could change in the near future. The Cardiff University study[25] on flexible demand in the British domestic electricity provides a projected figure for the electrical energy consumption in 2030, in terms of the breakdown of appliance-use, as shown on the bottom chart of Figure 9.

As can be observed from Figure 9, the mix of domestic appliance use is expected to carry on in a similar fashion; the Cardiff University study also claims that the overall sum of energy consumed domestically is expected to grow by approximately 10% from 113.1 TWh in 2012 to 124.6 TWh in 2030[25]. This is similar to National Grid's Future Energy Scenarios (FES)[26] estimate that the 2030 annual domestic demand will increase to between 112 to 126 TWh depending on the forecast scenario. In addition the FES estimates between 4 and 21 TWh electric vehicle demand by 2030. Driving 10,000 miles per year based on a typical consumption of 30kWh per 100 miles would correspond to a vehicle's annual consumption of 3000 kWh which is significant increase compared to existing average domestic consumption.

5.3 ZIP MODELLING OF APPLIANCES

One method used to model an appliance's performance characteristic with respect to its voltage and power is by the ZIP load modelling approach[27]. This model characterises each load type as either constant impedance (Z), constant current (I) or constant power (P). The ZIP model is described as a quadratic polynomial equation[28]:

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

Each appliance is described as having an element of *Z*, *I* and *P*, - in this case, the dominant of the three components is chosen to describe the appliance's behaviour under voltage-varying conditions. This makes it possible to determine the effect changes in supply voltage would have on each type of appliance as indicated in Table 4.

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[25] B. Drysdale, J. Wu and N. Jenkins, "Flexible demand in the GB domestic electricity sector in 2030," Cardiff, 2014.
[26] http://fes.nationalgrid.com/fes-document/
[27] http://www.enwl.co.uk/docs/default-source/class-documents/offline-demand-response-capability-assessment-final-report.pdf?sfvrsn=4
[28] K. Li, Y. Xue, S. Cui, Q. Niu, Z. Yang, P. Luk – "Advanced Computational Methods in Energy, Power, Electric Vehicles and Their Integration (Part 3)

Table 4 - ZIP parameters of typical appliances (dominant characteristic is highlighted by grey shading)[29 30 31]

Appliance	Constant Impedance (Z)	Constant Current (I)	Constant Power (P)
Refrigerator	1.17	-1.83	**1.66**
Fridge Freezer	1.17	-1.83	**1.66**
PC	0.00	0.00	**1.00**
LCD TV	0.00	0.00	**1.00**
Oven	**1.00**	0.00	0.00
Microwave	1.39	-1.96	**1.57**
Kettle	**1.00**	0.00	0.00
Electric Shower	**1.00**	0.00	0.00
Washing Machine	0.06	0.31	**0.63**
Tumble Dryer	**0.96**	0.05	-0.01
Other Power Electronic Devices (e.g. Phone Charger)	0.00	0.00	**1.00**
Compact Fluorescent Lamp Bulb	-0.01	**0.96**	0.05
GLS Bulb	0.47	**0.63**	-0.10

5.4 CONSIDERATION OF THE VARIATION OF DOMESTIC LOSSES WHEN SUBJECT TO VARIATIONS IN VOLTAGE AND HARMONIC LEVELS

Impact of Voltage Variations on Domestic Losses

Variation of supply voltages affects the current that flows and this affects losses in the domestic wiring network. In addition, the variation in voltage may affect the efficiency of the actual appliance. For example: Incandescent bulbs produce 70% of their intended luminous flux (dimming) at 10% below nominal voltage, and 140% of their intended luminous flux at 10% above nominal voltage.

Impact of Voltage Variations on Wiring Losses

The impact on domestic wiring network losses of voltage variations within the range discussed in Section 2.1 differ according to the load type;

- Constant impedance loads (Z): if impedance remains constant, Ohm's law dictates that a reduction in voltage also decreases the current. Reduction in current would result in a reduction in absolute I^2R losses in the wiring especially when the operating period of some constant impedance demands, such

[29] http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19596.pdf
[30] https://www.research.manchester.ac.uk/portal/files/32799596/FULL_TEXT.PDF
[31] ENWL/UoM - "WP2 Part A – Final Report 'Off-Line Capability Assessment'"

as an electric shower or incandescent lighting, would remain unchanged by the reduction in voltage. For example, if the voltage was reduced by 10% (from 100% to 90%), the current would also reduce by 10% (from 100% to 90%) and the wiring losses would reduce by 19% (1-0.92).

- Although a reduction in voltage could extend the operating period of constant impedance appliances controlled by thermostats, for example room heaters and ovens, absolute I^2R losses would still be less than associated with the higher voltage and higher current if the same amount of energy was delivered for both scenarios.
- Constant current loads (I): I^2R losses would not be affected when the current is constant and wiring losses would remain constant irrelevant of the supply voltage. Examples of constant current loads include compact fluorescent light bulbs, and cathode ray tube monitors/TVs27 which are no longer widely used.
- Constant power loads (P): devices which require a constant level of power delivery for their operation, due to $P = IV$, will experience alterations to the current they draw in cases where voltage is changed; decreases in system voltage will result in an increase of current being delivered to the device in order to maintain power delivery; absolute I^2R losses inherently increase due to greater current being transmitted through the domestic network wiring. For example, if the voltage was reduced by 10% (from 100% to 90%), the current would increase by 11% (90% x 111% = 100%) and the wiring losses would increase by 23% (1.112-1). Examples of constant power loads include switch mode power supplies and modern refrigerators.

It is assumed that customers' behaviour is not changed due to the impact of voltage variations, i.e. the customer still uses his lights for the same length of time despite it being very slightly dimmer due to a reduced voltage and they don't switch on additional lights to compensate.

Table 5 summarises the impact on absolute wiring losses for ZIP type loads subject to voltage reductions and increases.

Table 5 – Summary of impact on wiring losses for ZIP type loads subject to voltage variations

Load Type	Absolute wiring losses subject to decrease in voltage	Absolute wiring losses subject to increase in voltage
Z Constant Impedance	⇩	⇧
I Constant Current	No change	No change
P Constant Power	⇧	⇩

Impact of Voltage Variations on Appliance Efficiency

As variations in supply voltage have the potential to interact with various types of electrical appliances in different ways, depending on their electrical composition, it is important to consider the effects these variations could have on a case-by-case basis.

Although some appliances will consume the same amount of energy regardless of the supply voltage and others will consume less energy when the supply voltage is reduced, efficiency is not necessarily affected because the appliance's performance may be changed. For example, a LED light bulb may consume less energy when the supply voltage is decreased but the illuminance (productivity) is reduced so the corresponding efficiency is not changed. Alternatively, a refrigerator which absorbs less energy when the supply voltage is reduced whilst maintaining the same internal temperature would be considered to be more efficient at the lower voltage.

Appliance characteristics can help predict their behaviour and changes in efficiency when supplied by variations in voltage, however, the complexity of some appliance systems make such analysis difficult. For these more complex appliances, practical testing can provide useful information on the impact of variations in supply voltage on appliance efficiency. Such laboratory testing undertaken by EA Technology[32] has demonstrated that the sensitivity of efficiency to voltage variations can vary with the appliance type and manufacturer. For example, EA Technology tested two tumble dryers in their Voltage Optimisation study, which showed different impacts on their efficiency when the voltage was reduced[32]. The B rated tumble dryer showed a reduction in efficiency at a lower supply voltage, whilst the A+ rated tumble dryer showed a corresponding increase in efficiency. Consequently, it should be considered that although generalisations are valid, variations should be expected in the response of appliances to voltage variations.

For heating devices, such as electric showers, space heating, kettles and ovens, it is assumed that the efficiency is dominated by thermal aspects of the appliance and so changes in voltage do not significantly affect the efficiency of the appliance. However, a reduction in voltage would be accompanied by a reduction in current and consequential reduction in the I^2R losses within the appliance wiring, but this change is expected to have a negligible impact on the overall appliance efficiency.

Taking a kettle as an example; since a kettle is a constant impedance device, a reduction in the supplied voltage decreases the amount of current flowing and therefore the power supplied. It is assumed that the voltage reduction is within the permitted range discussed in Section 2.1 as the kettle may not operate correctly with supply voltages outside this range. The thermal energy required to boil the same volume of water remains constant regardless of the supply voltage, but the kettle needs to operate for a longer period of time when the supply voltage is lower. Thermal energy losses are likely to be similar for both cases due to kettle's thermal insulation and the short time required to boil the water. Although current will be flowing through the wire between the plug and the kettle's element for longer and the kettle's power light will be illuminated for longer, the associated losses in the wire and the energy consumed by the LED bulb would be comparatively small with respect to the energy required to heat the water. Hence the efficiency of the kettle remains similar, regardless of applied voltage within the permitted voltage range.

For appliances with motors, such as washing machines and tumble dryers, although some energy is consumed by the motor providing the rotation of the drum, most energy is consumed by the heater and its efficiency is unaffected by changes in voltage. The efficiency of the motor is expected to be dominated by mechanical factors, such as friction, which depend on the rotational speed. However, the operation of motors in older appliances and their efficiency can be affected by the supply voltage because a motor's torque depends on the square of the supply voltage. This sensitivity is not expected in modern appliances as their motors employ electronic controls which mean that their operation is unaffected by the supply voltage. The impact of a change in the I^2R losses in the wiring within the appliance is expected to have a negligible impact on the overall appliance efficiency.

Variations in voltage are expected to have a similar impact on the efficiencies of refrigerators and freezers. The efficiency and operation of compressors in older appliances, only, are expected to be affected by the supply voltage because the reciprocating compressors in modern refrigerators tend to be connected by inverters which make them less sensitive to the supply voltage. This is borne out of the findings from EA Technology's study[32] which tested refrigerators and freezers, and found that the most efficient refrigerator (A+++) did not experience a change in energy consumption or adverse effects in its performance when their supply voltage was reduced. When tested with a reduced supply voltage, less efficient refrigerators and freezers (A+ to A++) were found to consume less energy without affecting their performance, corresponding to an increase in efficiency.

The overall impact on the efficiency of older and less efficient refrigerators is dependent upon the magnitude of voltage variations away from nominal voltage, and the duration of these variations. Consideration should be given to whether such devices are disproportionately owned by lower income sectors of society.

Electronic devices, such as chargers for phones and modern TVs, tend to use switch mode power supplies to produce a low voltage DC supply. These devices are designed to work in different countries and can operate over a wide range of supply voltages, e.g. 110 - 230V. Consequently, the potential variation in supply voltage expected as operation of UK distribution networks changes is comparatively small. The electronic circuit configuration means that a change in supply voltage has little impact on the currents in most components and so the losses and efficiency are not significantly affected.

Electronics within LED lights rectify the AC supply to produce the DC supply voltage applied to the LED. This DC voltage is governed by the light's electronics and therefore is mainly unaffected by the AC supply voltage. Although the AC current and associated losses will be affected by the supply voltage, the AC circuit losses are so small that the overall efficiency of the LED light is expected to be unaffected by supply voltage magnitude. However, EA Technology's study[32] found that the effect on LED lights' energy consumption due to voltage variations depended on the manufacturer and type. Some LED bayonet light bulbs exhibited an increase in

[32] E. Dudek, EA Technology – "Voltage Optimisation", STP Module 5 Members 2013-14

efficiency at lower voltages; when supplied by a reduced supply voltage of 220V compared to 240V, their energy consumption decreased by 3% without any effect on illuminance (productivity). However, the LED lights showing the greatest reduction in energy consumption showed a corresponding reduction in illuminance, meaning that their efficiency was unaffected.

Table 6 summarises the impact on appliance losses when they are subject to voltage reductions and increases. Only the efficiencies of older appliances with motors are expected to be impacted by variations in the supply voltage, and the impact is expected to be small since the efficiencies of these devices are expected to be dominated by other factors such as insulation and mechanical parameters.

Table 6 – Summary of impact on appliance losses when subject to voltage variations

Load Type	Appliance losses subject to decrease in voltage	Appliance losses subject to increase in voltage
Heating Devices (Constant Impedance)	No change	No change
Appliances with Motors (older)	↑	↓
Appliances with Motors (modern - inverter connected)	No change	No change
Consumer Electronics	No change	No change
LED Lights	No change	No change

IMPACT OF HARMONIC VOLTAGE VARIATIONS ON DOMESTIC LOSSES

Impact of Harmonic Variations on Wiring Losses

Harmonic currents can be the source of significant losses in wiring systems. A report published by the EPRI Power Electronics Applications Centre[33] 1996 indicated that the distorted current increased losses in the wiring of a computer centre by about 2.3 times. It is recognised that these results may no longer be valid as the quality of electronics has improved in the meantime, however the quantity of power electronic devices is expected to be greater now.

[33] https://www.harmonicslimited.com/wp-content/uploads/2017/02/Harmonic-Currents-in-Building-Wiring.pdf

In the case of loads containing electric motors (washing machines, tumble dryers, etc.), harmonic currents can have a direct effect on the iron losses experienced within the motor stator. Hysteresis losses and Eddy current losses, the two major components of these iron losses, are a function of frequency and the square of the frequency, respectively. As such, higher frequency current harmonics will produce a greater level of iron losses within the motor. With the increase in the incorporation of power electronic devices on the domestic network – devices which often inherently operate using high switching frequencies – higher frequency harmonics will tend to become more present in the network, potentially giving rise to greater losses within these motors.

It could be argued that harmonic losses are affected more by customer choice than the impact of the harmonic voltage distortion level of the distribution network. In the domestic setting, losses will occur due to the harmonic currents injected by a customer's electronic devices and these losses are a consequence of the customer's choice of equipment they choose to employ, rather than the effect of the distribution network. Customer loads which do not contain power electronic interfaces – such as fixed impedance heating devices or mains-connected motors, will not inject harmonic currents but will draw harmonic currents from the supply, depending on the level of harmonic voltage distortion present. This distortion could be attributed to a combination of the power electronic devices connected within the customer's network and the background harmonic distortion present on the distribution network. Harmonic currents flowing in these fixed impedance/motor loads will cause losses in the domestic wiring network in addition to the I^2R loss due to the fundamental current. These harmonic currents may also have an effect on the efficiency of directly connected motors. Since these harmonic currents partly depend on customer connections, it could be suggested that customers have an ability greater than that of the DNOs to manage harmonic current losses within their distribution networks.

It is speculated that increases in the number of electronic devices in homes will mean that their harmonic currents will be the main source of harmonic currents within a domestic network, as evaluated in the assessment presented in Appendix B. Although equipment's harmonic currents are limited by BS EN 61000-3-2:2014- "Electromagnetic compatibility (EMC) Limits. Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)" it is estimated that the aggregated harmonic current due to all electronic devices in a home will be greater than the harmonic currents flowing in constant impedance devices due to the effect of background harmonic voltage distortion which is limited to the levels defined in Engineering Recommendation G5/4-1. Since harmonic currents and associated harmonic losses are likely to be dominated by effects of the customer's connections, the greatest influence on harmonic losses within domestic systems could come from choosing low harmonic current-injecting devices. The influence of DNO background harmonics is likely to be a secondary effect compared to that of the customer's devices.

The highest harmonic considered in Engineering Recommendation G5/4 is presently the 50th. It has been suggested that this could be increased to the 100th in the next revision, implying that the presence of higher order harmonics is expected to grow in the future. An increase in the number of consumer electronic devices (i.e. devices which tend to make use of power electronic components in their operation; which inherently produce harmonic currents) is likely to increase losses in domestic wiring networks due to harmonic currents.

Common sizes of conductors used in domestic wiring do not exhibit significant skin and proximity effects especially at low order harmonics. However, these effects could become more sizable at the frequencies corresponding to higher order harmonics. A consequence of this would be that the apparent conductor resistance and corresponding losses would be greater.

Impact of Harmonic Variations on Appliance Efficiency

Harmonics can also have an effect on the performance of various domestic appliances. For instance, in power electronic devices such as consumer electronics, harmonic currents can give rise to I^2R losses which cause undesirable heating of cabling and other electrical materials, such as within the dielectric material of capacitors. This can also have an effect on the life expectancy of such devices[34].

Another example of harmonics having an effect on the performance of domestic appliances is within motors. Harmonic distortion can cause oscillatory torques which cause mechanical oscillations and ultimately lead to wearing of mechanical components within the devices – reducing life expectancy, also generating unintended heat as a result. However, the impact of harmonics on motors is expected to decrease as more motors are controlled by inverters which provide some immunity to harmonic distortion in the supply voltage. Any effect of reduced motor efficiency on the efficiency of the overall domestic network would be small and decreasing because the energy consumed by such motors is only a small percentage of the total domestic consumption and is decreasing as they are replaced with inverter drive alternatives.

However, it is expected that the greater I^2R and motor losses due to increasing harmonic variations will have negligible impact on an appliances overall efficiency. This is because factors such as insulation and mechanical friction will dominate an appliance's overall efficiency and losses in the electrical components will be relatively small.

5.5 OVERALL SENSITIVITY OF DOMESTIC LOSSES VARIATIONS IN VOLTAGE

Having considered the voltage dependencies of the efficiency of a range of domestic appliance types with respect to their performance using the ZIP model, as well as the average household's energy consumption across these types of appliances both in 2012 and 2030 (predicted), it is possible to correlate the two in an attempt to understand the overall sensitivity of losses and efficiency across the domestic network. Based on the discussion with regards to the effect of voltage variations on the efficiency of appliances, it is assumed that the effect on losses is limited to losses in the domestic wiring.

[34] http://www.mantenimientomundial.com/sites/mm/notas/Harmonics.pdf

Table 7 shows the split of domestic power consumption with respect to appliance types, for both 2012 and the forecasted values for 2030, as well as each appliance type's ZIP model dependence and the impact on domestic wiring losses when the supply voltage is reduced from 100% to 90%.

Table 7 – Domestic appliance voltage dependence (2012 and 2030)

Appliance Type	2012 Consumption Split (%)	Predicted 2030 Consumption Split (%)	ZIP Model Dependence	Sensitivity of Efficiency to Voltage Reduction of 10%		
				Impact of wiring losses	Impact/Overall wiring losses 2012 split	Impact/Overall wiring losses 2030 split
Consumer Electronics	19%	21%	*P*	23.46%	4.46%	4.93%
Wet Appliances	13%	18%	*Z*	-19.00%	-2.47%	-3.42%
Cold Appliances	11%	8%	*P*	23.46%	2.58%	1.88%
Lighting	12%	10%	*P*	23.46%	2.81%	2.35%
Cooking	12%	11%	*Z*	-19.00%	-2.28%	-2.09%
Computing	6%	4%	*P*	23.46%	1.41%	0.94%
Space Heating	21%	21%	*Z*	-19.00%	-3.99%	-3.99%
Water Heating	7%	7%	*Z*	-19.00%	-1.33%	-1.33%
New Wiring Losses: at Voltage = 0.9pu					**0.20%**	**0.20%**

As can be observed within Table 7, in both 2012 and the predicted 2030 figures, the overall impact of reducing the voltage by 10% causes no change in domestic wiring.

5.6 ANALYSIS AND DISCUSSION

As determined through previous calculations, the 0.2% I^2R loss within a typical domestic wiring network is dwarfed by the potential energy consumption saving attainable by the user's choice in domestic appliance energy efficiency rating – by opting for an A++ rated appliance instead of an A rated appliance:

- 1.54% energy consumption reduction could be achieved for dishwashers;
- 3.65% energy consumption reduction could be achieved for tumble dryers;

as a percentage of the average annual energy consumption of 4192kWh.

In terms of the effects the variation of voltage levels has on domestic network wiring, the characterisation of different appliance types in terms of constant impedance, current and power by the ZIP model illustrates that the subsequent changes in current drawn by appliances in response to voltage variation could have an inherent effect on the level of I^2R losses encountered within the wiring. It has been estimated based upon consideration of the population of appliances that the effect of reducing the supply voltage by 10% will not affect the losses in the wiring network significantly.

Consideration of the impact of a future scenario where more consumer devices fall under the *constant power* category of the ZIP model (greater presence of power electronics and inverter connected motors) similarly showed that reducing the supply voltage by 10% will not affect the losses in the wiring network significantly.

This could be particularly noticeable if considered in conjunction with the effects of more widespread renewable distributed generation incorporation – causing the system to see greater overall voltage fluctuations due to changing conditions. In the case of solar PV generation, however, it would be reasonable to assume that these voltage fluctuations would be likely to balance out, seasonally; greater levels of generation with lower demand during summer, balanced with lower levels of generation but greater demand during winter.

The impact on domestic network losses of reducing the LV voltage limits needs to be considered in terms of the number of customers that would be affected and the time that they would operate outside of the present voltage limits. The extension of the voltage range would be more pronounced at the ends of circuits – therefore only some customers would experience voltages at the absolute extremes of the limits. WPD's Equilibrium project[35] has shown that if the lower HV voltage limit was decreased to -10% then approximately half of HV nodes would operate at voltages lower than the present -6% limits. Operation at the extremes of the limits would tend to occur only on a part-time basis, due to the variable nature of distribution network loading. WPD's analysis of daily and annual LV feeder loading has shown that it reaches its maximum for less than 3.24% of the year. Hence any impact on domestic losses due to the operation at low voltages is likely to be for a small proportion of time.

SENSITIVITY OF LOW CARBON TECHNOLOGIES TO VOLTAGE AND HARMONIC VARIATIONS

Transition to a low carbon future will involve the electrification of heat and transport. Increasing amounts of energy will be supplied to Heat Pumps and Electric Vehicles so their sensitivity to voltage and harmonic variations will be a significant component of the overall sensitivity of the domestic system.

[35] https://www.westernpower.co.uk/docs/Innovation/Current-projects/Network-Equilibrium/SDRC-1-Detailed-Design-of-the-enhanced-Voltage-Ass.aspx

Electric Vehicles

The overall efficiency of domestic systems will change with the connection of low carbon technologies such as heat pumps and electric vehicle chargers. Adoption of these technologies will increase a customer's consumption of electrical energy and the efficiency of their chosen battery charger and heat pump will affect the overall efficiency of their domestic network.

The charging systems for electric vehicle batteries, like other low-voltage consumer electronic devices, make use of switch mode power supplies. As such, the efficiency of such chargers is not expected to be affected by network voltage fluctuations. For home-charging, a new dedicated circuit would be added to the existing domestic network for the electric vehicle in accordance with BS 7671:2008 "The IET Wiring Regulations, meaning that the required cabling would be sized for the required amount of current flow. Also it is assumed that the circuit length would probably be short as the charger is likely to be installed close to the meter in the garage. Consequently, losses in the electric vehicle charger wiring is likely to be insignificant when compared to the round trip (charge/discharge cycle) efficiency of the car battery.

It is not expected that the efficiency of electric vehicle chargers will be affected by the presence of harmonic voltage distortion due to their use of electronics.

Solar PV

As solar PV panels produce DC power, an intermediate inverter is generally employed in order to export the generated power to the AC system. Similar to electric vehicle charging, the cabling installed between the inverter and the consumer unit is expected to be appropriately sized for this particular application (considering the expected output of the PV array, and therefore the expected current flow). Also, the cable length is expected to be short as the inverters tend to be in garages in order to be accessible without being inconvenient. For these reasons, PV wiring losses are expected to be insignificant, especially compared to the efficiency of the PV.

In terms of the UK power network as a whole, if the employment of PV generation is to continue to grow, the subsequent widespread employment of inverters (power electronic devices) is likely to contribute to the level of harmonics on the UK network, including higher order harmonics as indicated by the proposed revision of Engineering Recommendation G5.

Heat Pumps

Heat pumps utilise mains voltage to drive their compressor motors, many via an inverter, as well as a stepped-down supply (typically 24V via a built-in transformer) to drive their control circuits. For those with direct connected motors, the same effects on the performance on other appliances containing electric motors with respect to voltage/harmonic variations (as discussed previously) would be expected to occur in the electric motors of heat pumps.

A study by the University of Canterbury, New Zealand[36], on the performance of heat pumps when they experience under-voltages noted that the heat pumps with rectifiers tended to draw higher currents during periods of reduced voltage (during both heating and cooling modes), concluding that these devices typically operate as constant power devices. I^2R losses are increased due to the higher current drawn when the voltage is reduced. However, the increase in electrical losses is expected to be small compared to the thermal benefit provided by the heat pump.

POLITICAL INFLUENCE ON DOMESTIC UK ENERGY EFFICIENCY

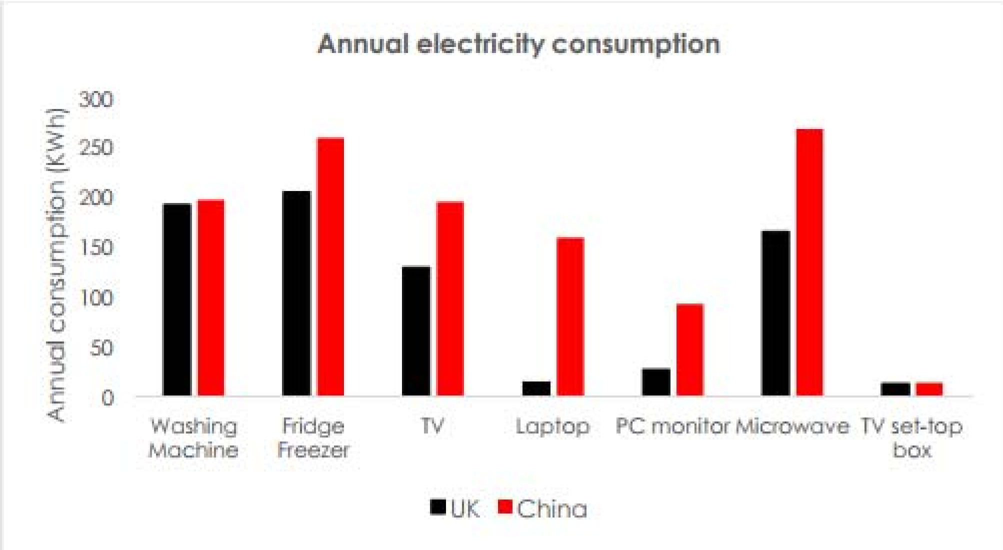
Political influences could have a significant impact on the domestic energy network. The country's decision to leave the EU could have a direct effect on this; the stringent EU laws regarding energy efficiency standards within domestic appliances may no longer be mandatory in the UK in the event of its relinquishment of EU membership.

With China being the world's largest producer of consumer electronics and domestic appliances, without adoption of legislation similar to that of the EU, it is predicted that the UK domestic appliance market could become flooded with cheaper Chinese equipment (due to the average consumer's natural propensity to purchase the lowest-cost product) of lower efficiencies, thus incurring higher domestic losses. Figure 10 illustrates that the average energy consumption of UK domestic appliances is less than the comparable Chinese appliance[37]:

[36] https://ir.canterbury.ac.nz/bitstream/handle/10092/10539/12647749_Heat_Pump_IET_Vdip_v10.pdf?sequence=2

[37] http://eciu.net/assets/Reports/ECIU_Appliance_Report-FINAL.pdf

Figure 10 – Annual electricity consumption of comparable domestic appliances: UK vs China[45]



An argument for focussing on improving the efficiency of UK domestic appliances – which the EU fully intends to continue to do via regulation – is a reduction in the loading of the energy network. Frontier Economics[38] suggests that placing such a focus on improving energy efficiency could be considered as an investment in the country's electrical infrastructure, delivering the view that these investments can be as effective at reducing pressure on the demand of power networks as installing new generation plants or storage systems.

To illustrate the effect improving appliance efficiency can have on a major power system, Greenpeace state that the switching of all lighting systems in the UK to LED-based systems could result in a reduction of 8GW of the country's electrical demand – more than the combined installed capacity of two of the country's newest nuclear power stations[45].

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[38] http://www.frontier-economics.com/documents/2015/09/energy-efficiency-infrastructure-priority.pdf

5.7 TASK 3 CONCLUSIONS

Task 3 - Conclusions

The way in which voltage/harmonic variations affect domestic networks varies depending upon the types of appliance. The categorisation of appliances with the ZIP model allows evaluation of how voltage variations may affect their performance, and how they influence network losses.

It is concluded that the overall efficiency of domestic systems is mainly insensitive to voltage. The efficiencies of most appliances are not significantly affected by variations in voltage partly because they are dominated by non-electrical factors such as insulation and mechanical parameters. Losses in wiring networks were found to be overall insensitive to voltage variations despite some appliances drawing more current, and others drawing less current, when the supply voltage is reduced. Even if it had been identified that wiring losses were sensitive to voltage variations the impact on the sensitivity of the overall domestic system would have been small because wiring losses are a small part of the overall efficiency of domestic systems.

The growing presence of power electronic devices, and other devices which require constant power delivery for their operation, implies that domestic networks could become less sensitive to voltage variations – and their power electronic nature could increase levels of harmonics within the network, resulting in greater I^2R losses in cabling.

Increasing harmonic currents are likely to increase losses in domestic wiring networks. This increase will mainly depend upon the harmonic currents injected by a customer's devices and the impact of the distribution network's background harmonics is likely to be secondary.

The efficiencies of future Low Carbon Technologies, including Heat Pumps, Electric Vehicles and PV, are not expected to be significantly affected by voltage and harmonic voltage variations since they employ electronic interfaces and their efficiencies are dominated by non-electrical factors.

The UK's future political situation could cause existing EU regulations regarding the energy efficiency of domestic appliances to be dropped. The consequential decrease in the average home's appliance energy efficiency would be much greater than any sensitivity to voltage and harmonic voltage variations.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The range of individual customer's supply voltages is expected to increase and voltage limits may be extended, without a significant impact on the operation of customers' appliances and the efficiency of domestic networks.

Previous and ongoing project work indicates a high probability that customers will experience a wider range of supply voltages at their point of connection as the networks accommodate new connections. Research has been carried out to determine both the reasons for and the feasibility of increasing the allowed voltage range in the UK. DNOs such as Scottish Power Energy Networks, Electricity North West and Western Power Distribution have examined increasing the allowed voltage on their distribution networks, and have been able to determine that the level of performance their customers received was not diminished. An increase in voltage range could provide useful distribution network capacity to accommodate new low carbon technologies and voltage headroom to permit more distributed generation to be connected to the distribution network.

Harmonic currents in domestic networks are expected to increase with a potential impact on the operation of customers' appliances and the efficiency of domestic networks.

Harmonic losses could be affected by increasing harmonic distortion which is alluded to by a number of factors. ENA's Engineering Recommendation G5/5 standard (still in consultation) has proposed to include consideration of harmonics up to the 100^{th} harmonic within the UK power system, suggesting that there is growing concern regarding harmonics and their effects on the distribution network in the future. The presence of greater levels of harmonics within any network incurs additional I^2R losses. The growing expectation that harmonics will increase is supported by predictions that the use of harmonic current-inducing consumer electronics will increase. The incidence of heavy-duty power electronic equipment involved in the utilisation of electric vehicles, could also play a contributing factor in this.

The efficiency of domestic systems is dominated by appliance efficiencies because losses in domestic wiring networks are small.

The overall efficiency of domestic systems is considered to be dominated by the efficiency of a customer's appliances rather than losses within the wiring network. Losses within the domestic network's wiring, calculated using a model of a typical installation, were found to be 0.2% of the energy supplied. This is small compared to the potential (1.16 to 3.65%) energy saving that can be achieved by opting for an A++ rated device over an A rated device.

Losses in domestic wiring networks were found to be insensitive to voltage variations.

It is concluded that voltage variations will have negligible impact on the losses in domestic wiring systems. By describing domestic appliances in terms of ZIP characteristics, alongside the predicted makeup of the UK's domestic energy use in 2030, it has been determined that lowering system voltage by 10% has no significant detrimental effect on the losses experienced within domestic wiring networks.

The efficiencies of modern domestic appliances employing electronics are mainly insensitive to voltage variations.

The fact that many of the devices used in domestic homes are designed to operate in a wide range of countries with different operating voltages and employ electronic interfaces indicates that many appliances are mainly insensitive to voltage variations. This together with an understanding that appliance efficiencies are dominated by non-electrical factors, supports the conclusion that varying the supply voltage would have a negligible impact on overall efficiency. Also, it should be considered that operation at extremes of voltages would only be for part of the year, is likely to involve higher and lower voltages than usual and will not affect all customers. However, it should be noted that EA Technology's tests[32] found differences in how the energy consumed by an appliance varied when supplied by different voltages. Consequently, it should be considered that although generalisations are valid, variations should be expected in the sensitivity of an appliance's efficiency to voltage variations.

Changes to the efficiency of domestic systems due to increased harmonic distortion are expected to be dominated by the effects of appliances rather than the impact of background voltage distortion.

Greater levels of harmonic distortion are likely to increase in harmonic losses in domestic wiring networks, however, it is speculated that the increase is mainly attributed to customer devices rather than the impact of the distribution network. Increases in the number of electronic devices in homes will mean that their harmonic currents will be the main source of harmonic currents within a domestic network, and harmonic currents due to the effect of background harmonic voltage distortion will be lesser.

The efficiency of domestic systems could be significantly impacted by political decisions. In the near future, the UK looks to relinquish its EU membership – leaving any EU energy regulations with it. As such, domestic appliances connected within the UK energy network may no longer have to follow the stringent, but efficiency-boosting, EU rules regarding their operation. The potential exists for poorly-regulated appliances to become common within UK domestic networks, having detrimental effects on the electrical efficiency of UK homes. In addition, political actions could incentivise the uptake of future low carbon technologies, such as heat pumps and electric vehicle chargers, which could have a significant impact on the overall efficiency of domestic systems.

Customer actions will dominate the efficiency of their domestic system rather than operation of the distribution network.

The efficiency and harmonic performance of the appliances chosen by customers significantly affect the overall efficiency of their domestic network. It is considered that distribution network operation will have a secondary effect on domestic system efficiency because domestic wiring network losses and the efficiencies of modern electronic and constant impedance appliances are not significantly affected by voltage variations and background harmonic distortion levels.

Overall, the impact of distribution network operation on the efficiency of domestic systems is expected to be negligible compared to the potential impacts due to customer choices or political drivers.

6.2 RECOMMENDATIONS

This exploration of the impact of voltage and harmonic variations on domestic customer losses has provided useful initial insight. The learning gained can be employed to inform DNO decisions and used to develop the "next steps".

DISSEMINATION OF KEY MESSAGES

- The learning that the impact of voltage and harmonic variations on domestic customer losses is likely to be a secondary effect compared to customer's choice of appliances should be usefully shared within the industry to inform how networks are operated and inform consideration of changing voltage and harmonic limits.
- The learning aligns with DNO support of campaigns to encourage customers' energy efficiency improvements.
- Learning should be communicated to the appropriate national bodies making regulatory and political decisions to provide further understanding of domestic system efficiencies.

QUESTIONS ARISING

- Is there a social split in the impact of the operation of the distribution network on domestic system efficiencies? Are customers with older appliances more affected due to the inherent sensitivities of such appliances?
- Could background harmonic voltage distortion be in excess of the planning limits and therefore be affecting domestic network losses significantly?

FURTHER CONSIDERATIONS

- Domestic wiring network losses should be modelled more accurately than estimated within this project, by simulating their behaviour using a higher level of granularity, i.e. minute by minute, and by considering harmonic current flows.
- A better understanding of the variation of appliance efficiencies with voltage and harmonic variations should be gathered by surveying manufacturers, including those of low carbon technologies such as electric vehicle chargers, heat pumps and PV inverters.
- Impacts of voltage and harmonic variations on distribution network losses should be considered. Distribution network losses are typically greater than losses in domestic wiring networks and therefore any impact could be much more significant.

Appendix A

MODEL DATA

Category	Circuit	Appliance	Socket
Washing	Downstairs Sockets	Washing Machine	D
	Downstairs Sockets	Tumble Dryer	C
Refrigeration	Downstairs Sockets	Fridge	G
Kitchen Appliances	Downstairs Sockets	Microwave	E
	Downstairs Sockets	Kettle	F
Cooker	Cooker	Cooker	Cooker
Consumer Electronics	Downstairs Sockets	TV	A
	Upstairs Sockets	TV	J
	Downstairs Sockets	Speaker	B
	Upstairs Sockets	Small Speaker	N
	Upstairs Sockets	Phone Charger	K
	Upstairs Sockets	Phone Charger	M
	Upstairs Sockets	Desktop PC	L
Lighting	Downstairs Lighting	Energy Saving Bulb	L1
	Downstairs Lighting	Energy Saving Bulb	L2
	Downstairs Lighting	Energy Saving Bulb	L3
	Downstairs Lighting	LED Bulb	L4
	Downstairs Lighting	LED Bulb	L5
	Downstairs Lighting	LED Bulb	L6
	Downstairs Lighting	LED Bulb	L7
	Upstairs Lighting	LED Bulb	L8
	Upstairs Lighting	LED Bulb	L9
	Upstairs Lighting	LED Bulb	L10
	Upstairs Lighting	Energy Saving Bulb	L11
	Upstairs Lighting	Energy Saving Bulb	L12
	Upstairs Lighting	LED Bulb	L13
	Upstairs Lighting	Energy Saving Bulb	L14
Shower	Shower	Shower	Shower

Circuit	Performance over 24 hours			
	Total Load Consumption (Wh)	I^2R Loss Wh Phase conductor	I^2R Loss Wh Neutral conductor	I^2R Loss Wh Total
Downstairs Sockets	5441	2.973	2.973	5.945
Upstairs Sockets	989	0.144	0.144	0.289
Downstairs Lighting	586	0.071	0.071	0.143
Upstairs Lighting	385	0.188	0.188	0.377
Cooker	1369	1.108	1.108	2.217
Shower	2750	6.645	6.645	13.289
Tails	11520	0.534	0.534	1.068
	11520	11.664	11.664	0.202%

Appendix B

ASSESSMENT OF HARMONIC CURRENTS

Harmonic currents in domestic networks

It is hypothesised that harmonic currents flowing in domestic networks are dominated by the harmonic currents injected by power electronic appliances, and that the harmonic currents flowing due to the effect of background harmonics on constant impedance demands are less.

Customer's appliances are assumed to fall into two categories as tabulated below.

	Category	Example	Assumed percentage split of annual energy supplied*
1	Equipment which inject harmonic currents due to their use of electronics	Inverter connected drives and chargers	43%
2	Equipment which sink harmonic currents when supplied by voltages containing harmonics	Constant impedance loads such as heaters and electric showers	57%

* based on Table 7

The far right column of the table gives the estimated percentage energy consumed by equipment in these two categories as a percentage of the total energy consumed. Constant impedance appliances consume slightly more energy over the year.

Category 1 – Devices which inject harmonic currents

The harmonic currents of domestic appliances which inject harmonic currents into the low-voltage system are limited by the values given in IEC 61000-3-2: Limits for harmonic current emissions (equipment input current ≤ 16A per phase). This standard classifies equipment into classes A to D and defines limits in terms of Amps and percentage of fundamental current. The limitations for Class C (lighting equipment) are expressed in terms of percentage of the fundamental and are judged to be the most stringent. The Class C harmonic current injection limits are summarised below.

Harmonic Order	Max. $I_{harmonic}$ (% $I_{fundamental}$)
2	2
3	30 x λ
5	10
7	7
9	5
11 ≤ n ≤ 39 (only odd)	3

λ is the circuit power factor

An appliance operating at the maximum allowable injection of all harmonics up to the 9th order would have a Total Harmonic Distortion, THD, value of 27.5%, calculated as follows(assuming power factor of 0.9):

$$THD\ (\%) = \sqrt{2^2 + 27^2 + 10^2 + 7^2 + 5^2 + 3^2} = 27.5\%$$

For the purpose of this simple assessment it is assumed that the Class C limits apply to all domestic equipment which injects harmonic currents. By applying these limits to all equipment which injects harmonic currents (Category 1), our assessment could be considered to be conservative in terms of the potential harmonic current injection.

So, 43% of equipment is assumed to have a potential associated current THD of 27.5%.

It is recognised that the aforementioned IEC standard defines limits and some equipment may operate well below the limits. However, it is speculated that the need to keep equipment costs down will mean that expense is not incurred in minimising harmonic injections and the harmonic injection limits may be approached.

Category 2 – Devices which sink harmonic currents due to harmonic voltage distortion

The harmonic currents in constant impedance loads depend on the level of background harmonics. Background harmonics are limited by Engineering Recommendation G5/4-1 – “Planning Levels For Harmonic Voltage Distortion and the Connection of Non Linear Equipment To Transmission and Distribution Networks in the UK”. The maximum permitted planning THD level is 5% for 400V (low voltage) systems. A 5% current THD occurs when a supply voltage with 5% THD is applied to a constant impedance demand.

So, 57% of equipment is assumed to have a potential associated current THD of 5%.

Analysis

If we now compare the overall harmonic current due to equipment that injects harmonic currents and the equipment which sinks harmonic currents, we get:

	Category	**Calculation**	**Harmonic current THD as Percentage of total fundamental**
1	Equipment which inject harmonic currents due to their use of electronics	0.43 x 0.275	**11.8%**
2	Equipment which sink harmonic currents when supplied by voltages containing harmonics	0.57 x 0.05	**2.9%**

The estimated current flowing through the domestic system due to equipment which injects harmonic currents is greater than the estimated current flowing in equipment due to the background harmonics.

Conclusion

The hypothesis is confirmed based on this simple analysis of maximum allowable harmonic currents and the assumed split of equipment which will inject harmonic currents and equipment which will sink harmonic currents.

It is recognised that this conclusion is made on the basis of the energy supplied which is taken to be a proxy for current magnitude.

The hypothesis is expected to be even more valid in the future when a greater percentage of demands will inject harmonic currents due to a greater use of electronic interfaces.

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