Analysis of the Technical Performance of C₂C Operation for HV Networks

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Steven Blair, Campbell Booth
University of Strathclyde

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Abbreviations

C₂C  Capacity to Customers
CAD  Computer Aided Design
CHP  Combined Heat and Power
CIM  Common Information Model
CPU  Central Processing Unit
CSV  Comma-Separated Values
DG   Distributed Generation
DINIS Distribution Network Information System
DSR  Demand-Side Response
ENWL Electricity North West Limited
HV   High Voltage (6.6 kV or 11 kV)
IPSA Interactive Power System Analysis
LF   Load Factor
LLF  Loss Load Factor
LV   Low Voltage (typically 400 V)
Ofgem Office of Gas and Electricity Markets
OHL  Overhead Line
NOP  Normally Open Point
Plt  Long Term Flicker
Pst  Short Term Flicker
pu   Per Unit
PV   Photovoltaic
RMS  Root Mean Square
RTU  Remote Terminal Unit
SD   Secure Digital
TDD  Total Demand Distortion
THD  Total Harmonic Distortion
UTC  Coordinated Universal Time

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Chapter 1: Executive Summary

This report evaluates the technical benefits of the Capacity to Customers (C2C) project, an Ofgem Low Carbon Network Fund project led by Electricity North West Limited (ENWL) in conjunction with several industrial and academic partners.

The objective of the C2C project is to test a combination of new automation technology, non-conventional network operational practices (i.e., increased network interconnection), and commercial demand-side response (DSR) contracts. These changes will allow ENWL to increase interruptible demand and generation connections on a selection of trial circuits without resorting to conventional reinforcement measures. The project will thereby “release” inherent spare capacity in the high voltage (HV) system in order to accommodate the future forecast increases in demand and DG, and will therefore assist in meeting the UK’s ambitious CO2 emission targets.

This report documents work undertaken by the University of Strathclyde to quantify the technical performance of C2C network operation on electrical distribution systems. Specifically, this report analyses the impact of C2C operation on available demand capacity, DG capacity, electrical losses, power quality, and fault levels. This has been achieved using simulation models based upon actual system data and through the analysis of power quality monitoring data gathered from a representative proportion of the C2C trial circuits. The results in this report determine the theoretical maximum limits and effects of C2C operation on the aforementioned criteria. Particular attention is given to quantifying the benefits of interconnected (closed-ring) HV network operation over conventional radial (open-ring) operation.

The simulation studies of actual C2C trial circuits have shown that C2C operation can release significant demand and DG capacity. On average, C2C operation can achieve up to approximately a 76% increase in demand and a 225% increase in DG, compared with defined base case scenarios. However, the results depend significantly on the individual circuit topologies, the thermal ratings of circuit sections, and load or DG locations. On average, Interconnected C2C operation (with closed HV rings) releases more demand and DG capacity when compared to Radial C2C operation (with radial HV feeders). Furthermore, a “holistic” system approach is required when considering the connection of load or generation; other technical factors (such as primary transformer ratings) or non-technical factors (such as cost-effectiveness) may affect the maximum capacity which can be released by a particular HV circuit.

The technical losses in the HV network arising from C2C operation have been compared with losses in a reinforced radial system. Losses may be reduced if the NOP is closed, i.e., if Interconnected C2C operation is adopted rather than Radial C2C operation. In some cases, the reduction is marginal because the locations of NOPs are already optimised to minimise losses for conventional radial HV network operation. Furthermore, the average reduction in losses due to Interconnected C2C operation diminishes as the level of connected interruptible demand increases. At the maximum levels of demand released by C2C, C2C operation leads to annual HV network losses of approximately 1%, as a percentage of demand. This is
approximately 0.3% higher than the equivalent losses assumed from conventional reinforcement of the radial networks, but this must be offset against benefits accrued in the intervening period between introduction of C\textsubscript{2}C and the time when the maximum C\textsubscript{2}C capacity is reached (which would span many years).

Power quality measurements from several locations throughout the ENWL network and spanning a significant period of the duration of the C\textsubscript{2}C trial have been analysed to compare the effects of Radial C\textsubscript{2}C operation and Interconnected C\textsubscript{2}C operation. Extensive validation of the monitoring data has been performed to ensure that the comparisons are sound. C\textsubscript{2}C operation is likely to have only a marginal impact on power quality. This has been confirmed through theoretical analysis of the likely change in voltage total harmonic distortion (THD) resulting from Interconnected C\textsubscript{2}C operation. In particular, the measurement data indicate that the worst case mean THD measured at LV, approximately 3%, is well within the planning level of 5%.

It has been demonstrated that C\textsubscript{2}C operation – even at the most extreme levels of released demand and DG – is unlikely to exceed HV design fault level ratings or restrict the future adoption of C\textsubscript{2}C.
Chapter 2: Introduction

2.1 “Capacity to Customers” project overview

Distribution networks must be equipped for a significant increase in future electrical demand, due to the continuing electrification of transport and heating to meet the UK’s ambitious CO\textsubscript{2} emission targets [1]. Furthermore, the proliferation of distributed generation (DG) can sometimes be inhibited by lack of available network capacity. The challenges associated with these developments must be met in a cost-effective manner and without undue environmental impact. It is also important that future capacity can be delivered without compromising network protection or the security of supply. This report describes the operation and quantifies the technical benefits of the Capacity to Customers (C\textsubscript{2}C) project, an Ofgem Low Carbon Network Fund project led by Electricity North West Limited (ENWL) in conjunction with several industrial and academic partners.

The objective of the C\textsubscript{2}C project is to test a combination of new automation technology, non-conventional network operational practices (i.e., increased network interconnection), and commercial demand-side response (DSR) contracts. These changes will allow ENWL to increase demand and generation connections on a selection of trial circuits – representing approximately 10% of its high voltage (HV) system – without resorting to conventional reinforcement measures. The project will thereby “release” inherent spare capacity in the HV system in order to accommodate the future forecast increases in demand and DG, whilst avoiding (or deferring) the cost and environmental impacts that are associated with traditional network reinforcement.

2.2 University of Strathclyde’s role and approach

This report documents work undertaken by the University of Strathclyde to quantify several technical aspects of C\textsubscript{2}C network operation on electrical distribution systems. Specifically, this report analyses the impact of C\textsubscript{2}C operation on available demand capacity, DG capacity, electrical losses, power quality, and fault levels. This has been achieved using simulation models based upon actual system data and through the analysis of power quality monitoring data gathered from a representative proportion of the C\textsubscript{2}C trial circuits. The results in this report determine the theoretical maximum limits and effects of C\textsubscript{2}C operation. Throughout this report, the approach taken to analyse each of the factors investigated is to present simplified examples which distil the main concepts of C\textsubscript{2}C operation and the associated learning outcomes, followed by detailed analysis for each of the circuits under study. Particular attention is given to quantifying the benefits of interconnected (closed-ring) HV network operation over conventional radial (open-ring) operation.

The results in this report are complemented by work by the University of Manchester and the Tyndall Centre which analyses the economic and carbon impact of C\textsubscript{2}C operation.
2.3 Relevant C\textsubscript{2}C project hypotheses

The work described in this report focuses on verification of the following C\textsubscript{2}C project hypotheses:

1. The C\textsubscript{2}C method will release significant capacity to customers from existing infrastructure.
2. The C\textsubscript{2}C method will enable improved utilisation of network assets through greater diversity of customers on the network ring.
3. The C\textsubscript{2}C method will reduce like-for-like power losses initially but this benefit will gradually erode as newly released capacity is utilised.
4. The C\textsubscript{2}C method will improve power quality resulting from stronger electrical networks.

2.4 Chapter organisation

Chapter 3 describes the maximum demand capacity which can be released by C\textsubscript{2}C operation. Chapter 4 applies a similar methodology to determine the maximum DG capacity released by C\textsubscript{2}C operation. The effects of demand growth and interconnected operation on HV system electrical losses are evaluated in Chapter 5. In Chapter 6, data from extensive network monitoring is analysed to quantify the impact of C\textsubscript{2}C operation on power quality, including the system voltage profile, harmonics, and flicker. The worst case impact of C\textsubscript{2}C operation on fault levels is evaluated in Chapter 7. Chapter 8 presents overall conclusions in the context of the relevant C\textsubscript{2}C hypotheses.
Chapter 3: Impact of C₂C Operation on Released Demand Capacity

3.1 Introduction

This chapter describes the methodology for establishing the network demand capacity limits for a defined base case scenario and for C₂C network operation, and thereby analyses the results, benefits, and impact that C₂C operation could bring to the HV network in terms of extra released capacity. It is important to understand the typical performance of HV circuits without C₂C operation, i.e., without interruptible load and without closed ring operation, which forms the base case scenario. Hence, the relative performance of C₂C operation — in terms of additional capacity released — is quantified for a number of scenarios. This chapter, along with Chapter 4 which examines the DG capacity released by C₂C operation, answers the following C₂C project hypotheses:

1. The C₂C method will release significant capacity to customers from existing infrastructure.
2. The C₂C method will enable improved utilisation of network assets through greater diversity of customers on the network ring.

The capacity improvement for each circuit, relative to the defined base case, has been determined for both “Radial C₂C” operation and for “Interconnected C₂C” operation, i.e., the effects of operating the network with a closed ring have been evaluated. Two complementary approaches for determining the capacity range which is released by C₂C operation have been used for each circuit: uniform demand growth at existing network locations, and non-uniform “point” loads at specific circuit locations. This process is summarised in Figure 1.

![Figure 1: C₂C demand capacity evaluation process](image)

Unless otherwise stated, in this chapter the term “capacity” refers to “demand capacity”.

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Section 3.2 describes the processes for determining the network capacity limits for various circuit configurations. Section 3.3 provides a simplified overview of the effects of C2C on HV network capacity using hypothetical, but illustrative, simulation models. The full results for a selection of actual HV circuits are presented in Section 3.4, and conclusions are drawn on these results in Section 3.5. The generic method for generating the simulation models by importing legacy circuit data is described in Appendix A.
3.2 Methodology for establishing base case and C₂C capacities

This section describes the methodology for evaluating HV circuit capacity limits, using IPSA [2] simulation models that have been created as described in Appendix A. The Python scripting interface for IPSA has been used to automate the process of applying this methodology to 36 HV circuit models.

3.2.1 Base case firm capacity

The present distribution system planning practice is to consider how loads will be supplied if a single circuit is out of service. Satisfactory “backfeed” arrangements are required to ensure customers’ security of supply and to minimise customer minutes lost. In practice, each HV feeder will interconnect to a number of adjacent feeders and, for ENWL networks, up to two switching operations are permitted following a fault to transfer load and restore supplies [3]. For this reason, i.e., due to the N-1 security of supply requirements in the UK, the full radial capacity of each HV feeder cannot be used because these circuits must have capacity reserved to supply additional load under reconfigured network conditions following faults on adjacent circuits.

For the purposes of this assessment, only the two feeders comprising each ring circuit, which are connected via a normally open point (NOP), have been modelled. It is initially assumed that these feeders would be expected to support each other’s loads in the event of an outage on one of the feeders (note that the impact of other backfeeds is considered later in this section). The worst case N-1 scenario is an outage of the first section from the primary substation on either radial feeder.

Each of the two possible worst case radial feeder configurations, illustrated in Figure 2, has an inherent capacity limit. In each case, the primary circuit breaker on the faulted feeder has been opened, simulating a fault on the first circuit section from the primary, and the NOP has been closed. At a particular level of demand, a radial feeder will experience a thermal constraint or a steady-state voltage below regulatory limits at one or more locations on the feeder.
The process for evaluating the initial firm capacity (before considering other backfeeds) for each ring circuit is as follows:

1. For each of the two reconfigured radial feeders (shown in Figure 2) associated with each of the 36 modelled ring circuits, linearly increase the load scaling factor until a thermal or voltage constraint is reached.
2. The total apparent power flow, expressed in MVA, in the first section of each feeder is recorded; this value indicates the maximum radial feeder demand.
3. The initial firm capacity is defined as the lower of the individual capacities from each of the two reconfigured radial feeder arrangements; this limit ensures that all loads can be supplied during any single cable or line outage.

However, there is a potential for the initial firm capacity to significantly underestimate the actual capacity of a ring circuit because the above process assumes that each feeder is restricted to just one backfeed to support load transfers during N-1 conditions. In reality, multiple backfeeds may be available. Therefore, the base case used in the studies of \( C_2C \) capacity includes an additional 30\% demand to account for the additional capacity which is available from other backfeeds. This will be referred to as the “base case firm capacity”. The value of 30\% has been calculated from comparison of historical peak demand and the calculated initial firm capacity for the 36 modelled circuits.

### 3.2.2 Additional C2C capacity

The use of “Radial C2C” or “Interconnected C2C” operation permits interruptible load to be connected to a circuit, in addition to the initial non-interruptible loading defined

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2 The primary busbar voltage is assumed to be 1 pu, i.e., 6.6 kV or 11 kV. The threshold for a voltage constraint at any location in the ring circuit is 0.94 pu, i.e., -6\%.

3 Specifically, some circuits experience a peak historical demand (as extracted from half-hourly primary feeder measurements from 2012) which is greater than the calculated initial firm capacity; the median difference equates to an increase of approximately 30\%. It is assumed that most feeders have the potential to transfer loads to more than one other feeder, even if a load transfer is not evident in the historical demand data. Therefore, an additional 30\% demand has been added to the initial firm capacity of all modelled ring circuits.
by the ring circuit’s base case firm capacity. The methodology for evaluating the additional capacity released by Radial C\textsubscript{2}C and Interconnected C\textsubscript{2}C operation, for uniform demand growth and for non-uniform demand growth (i.e., “point” loads), is described in the following subsections. The capacity released by Radial C\textsubscript{2}C or Interconnected C\textsubscript{2}C operation is reached when load grows until the first investment in circuit reinforcement is required.

3.2.2.1 Radial C\textsubscript{2}C capacity for uniform demand growth

The additional interruptible load is considered to be distributed proportionately at each existing load location, as illustrated in Figure 3. This uniform growth in demand could emulate a potential future scenario where loads such as electric vehicles and heat pumps are widely adopted. The level of interruptible load is linearly increased by applying a scaling factor, as described in Section A.4.3, until a thermal or voltage constraint occurs anywhere in the radial circuit. This is similar to the process described in Section 3.2.1 except that the worst case N-1 configurations do not need to be considered because C\textsubscript{2}C loads would be disconnected under these conditions. The total demand supplied by both feeders will constitute the “Radial C\textsubscript{2}C capacity”.

This pattern of demand growth represents an “averaging” of discrete new load connections over time, with the assumption that loads will tend to grow proportionately at existing load locations.

![Figure 3: Radial C\textsubscript{2}C operation with uniformly distributed interruptible loads](image)

3.2.2.2 Interconnected C\textsubscript{2}C capacity for uniform demand growth

The circuit configuration for Interconnected C\textsubscript{2}C operation is as described in Section 3.2.2.1, except with a closed ring, as shown in Figure 4. Similarly, the total demand supplied by both feeders will be referred to as the “Interconnected C\textsubscript{2}C capacity”.

![Figure 4: Interconnected C\textsubscript{2}C operation with uniformly distributed interruptible loads](image)
Figure 4: Interconnected C₂C operation with uniformly distributed interruptible loads

3.2.2.3 C₂C capacity for non-uniform demand growth

The scenarios presented in Sections 3.2.2.1 and 3.2.2.2 represent an increase in demand which is uniformly distributed and interruptible. This is useful for initially establishing and comparing the capacity released by C₂C for the trial circuits. However, connections are also made on a “discrete” and localised basis, particularly for relatively large industrial and commercial customers. Therefore, it is important that the simulations and analyses consider the practical capacity released by C₂C for each circuit for relatively large, localised loads. This has been evaluated by determining the capacity to “accept” a localised increase in demand at specific locations within each ring circuit. A “point” load, which is assumed to be interruptible, is added at these locations and its demand increased until a thermal or voltage constraint is introduced. The base case firm capacity is used as a consistent initial scenario, and point loads are tested for both Radial C₂C and Interconnected C₂C configurations. It is not necessary to test N-1 configurations because the C₂C loads would be disconnected under these conditions.

The following three locations per feeder have been identified for evaluating the point load capacity:

1. For each feeder, the secondary substation closest to the primary substation.
2. The secondary substations closest to each “side” of the NOP on each feeder. These locations should exhibit the greatest difference in point load capacity between Radial C₂C and Interconnected C₂C operation. For some feeders, point load location 1 (closest to primary) and 2 (closest to NOP) are very similar because the NOP is relatively close to the primary.
3. Some feeders include relatively long branches which are connected as a spur off the main feeder. The most extreme location (i.e., electrically furthest from the primary substation) for each feeder has been tested with a point load, because a load at this location is likely to produce the worst case voltage drops and release a lower capacity. Existing demand at the extremities of
these spurs is relatively small (typically rural domestic loads) compared to loads connected to the main feeder or close to the primary.

The potential point load locations, labelled A1-3 and B1-3 for feeders A and B respectively, for an illustrative circuit operating radially are shown in Figure 5. These locations remain the same for interconnected operation with the NOP closed. Each “pair” of point load connections (A1 and B1; A2 and B2; or A3 and B3) is tested together. This is because Radial C2C operation requires a connection on each radial feeder to appropriately test the capacity which is released; consequently, the same configurations are tested for Interconnected C2C operation.

![Figure 5: Potential point load locations for Feeder A and Feeder B for radial operation](image)

Point load connections are made in addition to the load connected for the base case firm capacity. For each point load configuration, for each circuit in both Radial C2C and Interconnected C2C operation, the capacity of each pair of load connections is increased by the same factor until a thermal or voltage constraint occurs anywhere on the two feeders. The following results are recorded:

- The maximum possible point load rating that can be connected before a thermal or voltage constraint occurs.
- The total circuit demand, as measured at the primary feeder circuit breakers (i.e., the sum of the demand for each radial feeder) for consistency with the results for uniform demand growth.
- The type of constraint (thermal or voltage) experienced at the maximum point load rating.
3.3 Demonstration of interconnection and C₂C operation on network capacity using a simplified HV network

This section provides a simplified overview of the effects of C₂C on HV network capacity using hypothetical, but illustrative, simulation models. The differences and subtleties between Radial C₂C and Interconnected C₂C operation, in terms of capacity released, are highlighted along with the sensitivities of the released capacity.

3.3.1 Simplified HV network and assumptions

Figure 6 illustrates a simplified, but representative, HV network with the following properties:

- A simplified 11 kV network comprised of two feeders, with two secondary substations per feeder.
- A thermal rating of 5 MVA has been used for all branches.
- Initially, a 1 MVA load, with 0.95 lagging power factor, is connected at each secondary substation. This represents an arbitrary, nominal level of loading.
- Initially, all branches have the following positive sequence impedances: \( R = 0.1 \, \text{pu} \), \( X = 0.1 \, \text{pu} \) (on a 100 MVA base). As a result, the voltage drops across branches are relatively small and therefore voltage constraints do not occur. The branch associated with the NOP (if connected) has the same impedance as all other branches.

For simplicity, the examples given in this section do not include the effects of voltage constraints or of different branch thermal ratings, which are relevant considerations in actual HV networks. The relevant branch power flows and bus voltages are indicated on Figure 6 and throughout this section.
Three scenarios are considered with reference to the simplified HV network, as illustrated in Figure 7:

1. Symmetric feeder impedances and symmetric loads: both feeders are identical, i.e., have the same branch impedances and connected loads.
2. Asymmetric feeder impedances and symmetric loads: the impedances of the branches of feeder A are increased to: $R = 0.5\ \text{pu}$, $X = 0.5\ \text{pu}$; this emulates an increase in feeder length. The connected loads are identical. The NOP branch is shown as being longer in Figure 7, but it is not modelled as being longer.
3. Symmetric feeder impedances and asymmetric loads: each of the loads connected on feeder A are doubled to 2 MVA. All branch lengths (i.e., impedances) remain equal.

![Scenario configurations](image)

**Figure 7: Scenario circuit configurations**

### 3.3.2 Comparison of radial and interconnected operation under different scenarios

This section illustrates the effect of moving from radial to interconnected operation only, and describes the resulting effect on network power flows. The circuits are not at maximum loading, i.e., C2C operation has not been applied to the circuit.

**3.3.2.1 Scenario 1 – Symmetric feeder impedances and symmetric loads**
Due to symmetrical impedances and loads, closing the NOP has no effect; there is no power flow through the branch associated with the NOP, as shown in Figure 8.

3.3.2.2 Scenario 2 – Asymmetric feeder impedances and symmetric loads

For radial operation, the total demand on feeder A is fractionally higher (approximately 20 kVA) than for scenario 1 due to the additional losses experienced on feeder A as a consequence of its increased impedance.

For interconnected operation, closing the NOP causes a proportion of the demand on feeder A to be supplied from feeder B (the relatively low impedance feeder) via the NOP. Consequently, the power flows in feeder A are reduced. The worst case secondary substation voltage is improved compared to radial operation, from 0.981 pu to 0.993 pu.
3.3.2.3 Scenario 3 – Symmetric feeder impedances and asymmetric loads

In this case, closing the NOP allows the more lightly-loaded feeder prior to interconnection (feeder B) to supply a proportion of the load current of the other feeder via the NOP.

3.3.3 Maximum capacity released under different scenarios for C₂C operation

This section assesses the maximum capacity released for each scenario, for both Radial C₂C and Interconnected C₂C. All loads are scaled up in a distributed fashion until a thermal constraint occurs, as described in Section 3.2.2. A red box around a branch’s power flow label illustrates the presence of a thermal constraint.

3.3.3.1 Scenario 1 – Symmetric feeder impedances and symmetric loads

Closing the NOP has no effect on the maximum capacity of the ring circuit, which is 10 MVA in both Radial C₂C and Interconnected C₂C configurations.

3.3.3.2 Scenario 2 – Asymmetric feeder impedances and symmetric loads
For Radial C\textsubscript{2}C operation, feeder A experiences slightly higher losses than feeder B due to feeder A’s increased impedance. Consequently, the maximum Radial C\textsubscript{2}C capacity is dictated by the thermal rating of the first branch of feeder A (5 MVA). Therefore, the total capacity released by Radial C\textsubscript{2}C operation is 9.9 MVA, slightly lower than theoretical maximum of 10 MVA for symmetric feeders (scenario 1). However, it should be noted that circuit sections with relatively high impedance will tend to have lower thermal ratings, but for simplicity this factor is ignored in this section.

For Interconnected C\textsubscript{2}C operation, the asymmetry of the feeder impedances increases the power flow through feeder B and thereby “accelerates” the occurrence of a thermal constraint in the first branch of feeder B. Therefore, the maximum demand released by Interconnected C\textsubscript{2}C operation, 6.9 MVA, is significantly lower than the maximum capacity for Radial C\textsubscript{2}C operation of 9.9 MVA.

3.3.3.3 Scenario 3 – Symmetric feeder impedances and asymmetric loads
Figure 13: Scenario 3 – Radial C2C (left) and Interconnected C2C (right)

For Radial C2C operation, the maximum capacity is limited by the heavily-loaded feeder. Therefore the maximum Radial C2C capacity is 7.6 MVA. Note that feeder B is relatively underutilised.

For Interconnected C2C operation, feeder B supplies a proportion of the demand connected to feeder A due to the impedances of the interconnected system. The total capacity is limited by the first branch of feeder A. The maximum capacity released by Interconnected C2C operation, 8.9 MVA, is therefore higher than the maximum Radial C2C capacity for this scenario.

3.3.4 Overview of results for the simplified HV network

Table 1 summarises the maximum demand released by Radial C2C and Interconnected C2C for each scenario, using the simplified HV network.

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<th>Scenario 3</th>
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<tr>
<td>Interconnected C2C</td>
<td>10 MVA</td>
<td>6.9 MVA</td>
<td>8.9 MVA</td>
</tr>
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Table 1: Summary of maximum released demand

The following can be concluded:

- If the two feeders comprising the ring circuit are perfectly symmetrical (scenario 1), which is highly unlikely in practice, there is no difference in the capacity released by Radial C2C or Interconnected C2C; closing the NOP has no effect.
- If one of the feeders comprising the ring circuit has a higher impedance than the other (scenario 2), Radial C2C will generally release more demand capacity than Interconnected C2C.
- If one of the feeders comprising the ring circuit is more heavily-loaded (scenario 3), Interconnected C2C will generally release more demand capacity than Radial C2C.
For simplicity, the effects of combinations of feeder impedance and load asymmetry are not demonstrated in this section. However, the following general results can be noted:

1. **Feeder A higher loading, feeder A higher impedance**: interconnected operation can significantly affect feeder power flows; feeder B supplies a significant proportion of the power, via the NOP, to loads connected to feeder A. The circuit sections near to the NOP require the thermal capacity to support this additional power flow. The worst case voltage on feeder A is significantly improved (e.g., from 0.952 pu to 0.986 pu) by closing the NOP. For this scenario, the suitability of Radial C2C or Interconnected C2C operation, in terms of maximising released capacity, depends on the parameters of the specific circuit.

2. **Feeder A higher loading, feeder B higher impedance**: interconnected operation allows feeder A to supply a proportion of the power to load connected to feeder B, via the NOP. This “accelerates” the occurrence of a thermal constraint on the first circuit section of feeder A (which is already relatively heavily loaded), similar to scenario 2. Therefore, in terms of maximising released capacity, Radial C2C may be preferable to Interconnected C2C operation for this feeder and load configuration.
3.4 Results for ENWL C2C trial circuits

3.4.1 C2C capacity for uniform demand growth

3.4.1.1 Overview of results

Based on analyses of the modelled circuits, Figure 14 illustrates the increase in total demand which is possible using C2C operation, for both radial and interconnected modes of operation, relative to the previously-established base case firm capacity for each ring circuit. The distributions of these results are visualised using box plots, where the coloured box illustrates the range between the first and third quartiles (Q1 and Q3, respectively), and the median value (Q2) is shown as a black line within the coloured box. The ends of the “whiskers” represent the extreme values within 1.5x the interquartile range, i.e., within $1.5 \times (Q3 - Q1)$. Any outliers, defined as lying outside 1.5x the interquartile range, are represented as blue crosses. The mean values are represented by black dots and are labelled.

The N-1 requirement for conventional operation restricts the utilisation of circuit capacity and the deployment of C2C makes significantly better use of the existing assets: a mean increase of 59% for Radial C2C operation and a mean increase of 66% for Interconnected C2C operation. For clarity, a 100% increase represents a doubling in demand.

The results in Figure 14 highlight that there is significant variation in the available capacity released by C2C operation across all 36 circuits (an increase ranging from 0% to 184%) because the capacity depends significantly on the circuit topology, the load distribution, and the base case firm capacity. For example, a circuit which is relatively heavily loaded near the NOP of the two individual radial feeders would be expected to benefit the most from Interconnected C2C operation.

Table 2 summarises the type of constraint – thermal or voltage – experienced by each circuit for uniform demand growth. For both Radial C2C and Interconnected C2C operation, a greater proportion of circuits are limited by thermal capacity rather

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4 These values have been obtained by calculating the percentage increase (relative to the base case firm capacity) for each circuit, and then calculating the mean of these values.
than by a voltage constraint, compared with the base case. This is due to the occurrence of voltage constraints during the worst case N-1 configurations (see Figure 2) which must be considered for the base case, but are avoided for C\textsubscript{2}C operation because additional C\textsubscript{2}C loads are disconnected when the system is operating in an N-1 configuration.

<table>
<thead>
<tr>
<th></th>
<th>Thermal constraints</th>
<th>Voltage constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>67%</td>
<td>33%</td>
</tr>
<tr>
<td>Radial C\textsubscript{2}C</td>
<td>81%</td>
<td>19%</td>
</tr>
<tr>
<td>Interconnected C\textsubscript{2}C</td>
<td>89%</td>
<td>11%</td>
</tr>
</tbody>
</table>

Table 2: Proportion of constraint types for 36 ring circuits for uniform demand growth

Section 3.4.1.2 analyses the differences between Radial C\textsubscript{2}C and Interconnected C\textsubscript{2}C operation. The cause of the large range for capacity increase values is analysed in Section 3.4.1.3.

3.4.1.2 Comparison of Radial C\textsubscript{2}C and Interconnected C\textsubscript{2}C operation

Figure 15 illustrates the increase in demand for all 36 modelled circuits. Although Interconnected C\textsubscript{2}C operation releases more capacity than Radial C\textsubscript{2}C operation on average, there are specific circuits where Radial C\textsubscript{2}C operation releases more demand capacity. It is important to note that these results assume a uniform, distributed addition of interruptible demand.

To illustrate the differences between Radial C\textsubscript{2}C and Interconnected C\textsubscript{2}C operation, diagrams (or “graphs”) of the “St Annes” circuit are given in Figure 16 and Figure 17, respectively. The graphs represent HV substations as vertices (the circles), with the primary substation highlighted with a label (at the bottom left). The substation locations are geographically accurate, relative to each other. The width of each edge (the lines inter-connecting the circles) represents the thermal capacity, and the radius of each substation represents the total connected load. The colour of each edge represents the thermal headroom of each circuit section as a gradient from yellow (full headroom) to red (no headroom). The shading within each circle is representative of the voltage magnitude, with solid black representing 1 pu and a white circle representing 0.94 pu.
It can be observed that the first circuit section of feeder A, as labelled in Figure 16, experiences a thermal constraint for Radial C2C operation, but feeder B is relatively underutilised. Conversely, for Interconnected C2C as shown in Figure 17, feeder B is able to supply a proportion of the load connected to feeder A via the (closed) NOP. Therefore, for this circuit arrangement, the maximum total demand (indicated by the size of the vertices) is significantly higher for Interconnected C2C operation due to the “balancing” of the power flows in each feeder. This is similar to scenario 3 in Section 3.3.

Figure 16: Graph of St Annes circuit for Radial C2C operation (maximum demand)

Figure 17: Graph of St Annes circuit for Interconnected C2C operation (maximum demand)

To illustrate why, for some circuits, Radial C2C can release more capacity than Interconnected C2C, graphs of the “Whalley Range” circuit are presented in Figure 18 and Figure 19. The loads connected to each feeder are approximately
symmetrical, and therefore the first circuit sections of both feeders A and B in Figure 18 are at (or close to) the maximum thermal capacity. This indicates that, in this case, Radial C2C operation is effective at maximising the utilisation of the HV circuits.

Conversely, Interconnected C2C operation causes a change in the power flows due to closing the NOP, which results in the first circuit section on feeder A carrying a relatively higher proportion of the total load current, compared to the base case. As shown in Figure 19, this limits the capacity released for Interconnected C2C because closing the NOP inherently reduces the thermal headroom in feeder A. This is similar to scenario 2 in Section 3.3.

![Figure 18: Graph of Whalley Range circuit for Radial C2C operation (maximum demand)](image)
3.4.1.3 Analysis of range of capacity results

Figure 15 illustrates the extent of the capacity above the base case firm capacity evaluated for Radial C2C and Interconnected C2C operation. It shows a wide range in the results and two example circuits, “Middleton Junction” and “Monton”, are examined here as a way of explanation.

The analysis of the Middleton Junction circuit does not show C2C operation to release any additional capacity for either Radial C2C or Interconnected C2C, relative to the base case firm capacity. This is because connection of the base case firm capacity of the circuit results in each feeder being loaded close to its rating; there is no spare capacity, even in system normal arrangement. The 30% factor in the evaluation of the base case firm capacity has a significant influence in this situation.

The Middleton Junction circuit is illustrated as a graph in Figure 20, for the base case firm capacity with the NOP open. It can be observed that one of the feeders (labelled “B”) is relatively heavily loaded and any further loading on this feeder beyond the
base case firm capacity would result in a thermal constraint. Therefore, no interruptible C\(_2\)C demand can be connected to the ring circuit for because a thermal constraint would be experienced on feeder B (and the results show that interconnection does not change power flows significantly).

Conversely, the Monton ring circuit releases significantly more capacity for both Radial C\(_2\)C and Interconnected C\(_2\)C operation, relative to the base case firm capacity, due to a voltage constraint which significantly limits the base case firm capacity (shown in Figure 21) during the worst case N-1 configuration. Additional interruptible demand can be connected during system normal conditions, avoiding the configuration which results in this voltage constraint.

The results for the Middleton Junction and Monton circuits illustrate that the base case firm capacity has a significant impact on the apparent percentage capacity increase released by C\(_2\)C operation: 0% and 169%, respectively for Interconnected C\(_2\)C.
### 3.4.2 C₂C capacity for non-uniform demand increase

Figure 22 illustrates the distributions of point load capacity for each of the three point load locations studied, alongside the results for uniform demand growth presented in Figure 14. The mean value for each distribution is represented by a black dot. The x-axis is the increase in demand, as a percentage relative to the base case firm capacity.

![Box plots of maximum C₂C demand capacity](image)

Interconnected C₂C operation is generally more favourable for supporting point loads, compared to Radial C₂C operation. For example, Interconnected C₂C operation generally permits larger point load connections at locations near the NOP (locations A2 and B2), i.e., on average 63% compared to 57% for Radial C₂C. This is due to both feeders being able to supply load current to the point loads, which generally mitigates thermal constraints, rather than just one feeder as under Radial C₂C operation. Furthermore, at the extremities of circuits (locations A3 and B3), Interconnected C₂C can typically release more capacity than Radial C₂C, 50% compared to 44%, which illustrates that closed ring operation can provide greater flexibility in accommodating additional demand.

Lower amounts of C₂C point load can be connected at the (electrically) furthest locations from the primary, A2+B2 and A3+B3, because more remote feeder sections are likely to be of lower capacity (due to the “tapered” design of most HV feeders), and therefore reach a thermal or voltage constraint before upstream, higher-capacity, feeder sections. This is illustrated by the fact that the average additional demand released at locations A1 and B1 is higher than at locations A2 and B2, which is in turn higher than at locations A3 and B3.
Figure 22 illustrates how the “localisation” of demand can affect the released capacity, compared with uniform load growth. For example, at locations A1 and B1, the point load capacity is higher than assuming uniformly demand growth. Point load locations A2 and B2 release slightly less capacity compared to uniform growth and locations A3 and B3 release significantly less capacity (as would be expected from the relatively high impedance between the point of connection and the primary).

3.4.3 Impact of Interconnected C2C operation on demand diversity

The studies in this chapter assume that the maximum demand connected to each feeder occurs at the same time, without diversity. Interconnected C2C operation has the potential to increase the diversity of demand connected to a ring circuit, i.e., the demand profile over time on feeder A may tend to complement – rather than coincide with – the demand on feeder B, yielding further capacity headroom within the ring circuit. The “demand diversity factor” of the HV ring circuit is defined as:

\[
\text{demand diversity factor} = \frac{\text{peak of feeder A demand} + \text{peak of feeder B demand}}{\text{peak of aggregate demand}}
\]

The aggregate demand is the sum of the half-hourly measurements of both feeders. A demand diversity factor value of 1 is the worst case, indicating that the individual feeder peak demands tend to coincide. A value of 2 is the theoretical best case, indicating that the feeder peak demand values are similar, but the feeder demands are “fully” diverse (which is obviously not likely in practice).

Using half-hourly feeder current measurement data from the year 2012, Figure 23 presents a histogram of the demand diversity factor for each of the 36 modelled ring circuits. On average, the demand diversity factor is 1.081, which shows that there is potential for a slight improvement in diversity due to interconnected operation.

![Figure 23: Histogram of demand diversity](image-url)
3.5 Conclusions

This chapter has described the methodology and results for evaluating the HV network capacity benefits of C2C. A base case has been established which represents the maximum demand that can be connected to a pair of radial HV feeders, without deploying C2C. The capacity increases, relative to the base case, which can be achieved by the deployment of Radial C2C (open ring) operation and Interconnected C2C (closed ring) operation, have been evaluated.

Two complementary methods of modelling additional, interruptible C2C load capacity have been investigated:

1. Uniform demand growth, perhaps reflective of a high penetration of loads such as heat pumps and electric vehicles, which are relatively evenly distributed throughout existing load locations.
2. Non-uniform “point” loads, which may be reflective of relatively large localised loads such as new industrial or commercial customers.

From the results, the following can be concluded:

- For either Radial C2C or Interconnected C2C operation, the released capacity depends on the location of existing and additional demand, the circuit topology, and the thermal rating of individual circuit sections.
- On average, the practical demand released by Radial C2C should be expected to be up to approximately 44-70% greater than the base case firm capacity.
- On average, the practical demand released by Interconnected C2C should be expected to be up to approximately 50-76% greater than the base case firm capacity.
- Interconnected C2C operation generally accommodates more demand capacity than Radial C2C operation, when considering all demand scenarios including uniform growth, and point loads connected near the NOP or at circuit extremities. This occurs because Interconnected C2C operation typically supports configurations where one feeder is relatively more heavily loaded than the other feeder comprising the ring circuit; the lower-loaded feeder can supply load current to the other feeder, via the NOP. Such configurations are not possible with Radial C2C, without circuit reinforcement.
- In some cases, Radial C2C operation can lead to underutilisation of one of the HV feeders comprising the ring circuit. This is because the adopted methodology considers that each individual feeder cannot be loaded up to its limit, independently of the other feeder; both feeders are limited by a constraint on either feeder. If the NOP location was re-selected to “balance” the two feeders, then these scenarios (where load is concentrated on one feeder) would generally be avoided – meaning that Radial C2C operation would always be preferable in order to maximise released demand.
- In some cases, Radial C2C operation can release more capacity than Interconnected C2C. This generally occurs when one feeder comprising the ring circuit has a higher impedance than the other feeder, i.e., where the NOP is not located at the electrical midpoint of the ring circuit.
- The “localisation” of demand connections can affect the released capacity, compared with uniform load growth. Due to the “tapered” design of HV feeder thermal ratings, greater capacity is released for demand concentrated closer to the primary compared to demand concentrated at more remote locations.

- As illustrated for C2C DG capacity in Chapter 4, C2C operation has the potential to accommodate a significant increase in demand in HV circuits, and therefore confirms the first C2C project hypothesis that: “the C2C method will release significant capacity to customers from existing infrastructure”. Furthermore, the increase in demand capacity from the use of DSR and the improved opportunity for demand diversity (as demonstrated in Section 3.4.3) validate the second C2C project hypothesis that: “the C2C method will enable improved utilisation of network assets through greater diversity of customers on the network ring”.

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Chapter 4: Impact of C2C Operation on Released DG Capacity

4.1 Introduction

This chapter describes the methodology, results, and analysis of a simulation study to evaluate the distributed generation (DG) capacity released by C2C operation applied to 36 actual circuits. A DG “base case” is established which defines the maximum DG which can be connected to circuits without C2C operation, i.e., when there is a requirement for DG to remain connected during N-1 conditions. Therefore, the additional DG which can be connected for C2C operation – where DG may be disconnected during N-1 conditions – can be quantified. This chapter complements the evaluation of C2C demand capacity described in Chapter 3, and contributes to answering the following C2C project hypothesis: “the C2C method will release significant capacity to customers from existing infrastructure”.

The DG capacity improvement for each circuit, relative to the DG base case, has been determined for both “Radial C2C” operation and for “Interconnected C2C” operation, i.e., the effects of operating the network with a closed ring have been evaluated. Two complementary approaches for determining the range of DG capacity which is released by C2C operation have been used for each circuit: distributed, uniform DG growth at existing network locations, and localised, non-uniform “point” DG connected at specific circuit locations. This process is summarised in Figure 61.

Section 4.2 describes the processes for determining the network DG capacity limits for various circuit configurations. Section 4.3 provides a simplified overview of the effects of C2C on HV network DG capacity using hypothetical, but illustrative, simulated scenarios. The full results for a selection of actual HV circuits are presented in Section 4.4, and conclusions are drawn on these results in Section 4.5.
4.2 Methodology for establishing DG base case and C\textsubscript{2}C capacities

4.2.1 Overview of methodology

Two complementary approaches have been used to quantify the potential increase in DG capacity released by C\textsubscript{2}C operation:

1. Uniform growth in DG at all existing secondary substations. This approach is representative of distributed domestic photovoltaic (PV) connections.
2. Non-uniform growth, with DG at just one specific secondary substation on each feeder. This approach is representative of large new DG connections such as wind farms, combined heat and power (CHP), or biomass.

These approaches are intended to mirror the approaches used for evaluating the C\textsubscript{2}C demand capacity. The DG base case, which is used as a reference for quantifying the increase in DG capacity released by C\textsubscript{2}C operation, is described in Section 4.2.2. Sections 4.2.3 and 4.2.4 describe the methodologies for evaluating uniform and non-uniform DG growth respectively.

4.2.2 DG base case and assumptions

The N-1 circuit configurations used to determine the DG base case are illustrated in Figure 25. The initial connected DG capacity at each secondary substation is proportional to the initial connected demand (which is based on transformer ratings or maximum demand indicators), i.e., it is assumed that DG penetration is proportional to maximum demand levels. For example, it is assumed that domestic PV would generally be connected in proportion with existing domestic demand. DG is modelled to export constant power at unity power factor (see Appendix B for a discussion of the effects of other power factors). The DG connected at all secondary substations is increased until a thermal or voltage constraint occurs on the HV network. The particular N-1 configuration (from the two possible options) from Figure 25 which supports the lower total generation export is selected as the DG base case.
No demand is modelled for simulations involving the DG capacity. A maximum HV voltage limit of 1.012 pu is assumed based upon the present HV planning methodology for assessing DG connections\(^5\).

4.2.3 C\(_2\)C operation for uniform DG growth

All connected DG capacity, as established for the DG base case, is uniformly scaled up (using the same multiplicative factor at every DG location) until a thermal or voltage constraint is encountered anywhere in the modelled HV network. This is performed for Radial C\(_2\)C operation (Figure 26) and Interconnected C\(_2\)C operation (Figure 27) to establish their respective released DG capacities. For Radial C\(_2\)C operation, the released DG capacity could be limited by a constraint on either of the two feeders because this represents the level of DG growth where the first reinforcement investment would be required.

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\(^5\) This is based on the LV voltage statutory upper limit of 230 V +10% in the UK, and an assumed distribution transformer ratio of 11000:250 (for 11 kV systems) [28]. Therefore, a 1.2% (0.012 pu) increase in HV voltage above nominal results in the maximum allowable LV voltage of 253 V.
4.2.4 C<sub>2</sub>C operation for non-uniform DG growth

Figure 28 illustrates representative locations for specific (or “point”) DG connections. Two representative locations have been selected: the secondary substation at the NOP, and the secondary substation at the furthest extremity from the primary (e.g., at the end of the longest spur). The same locations have been used for “point” loads in the C<sub>2</sub>C demand capacity evaluation methodology in Chapter 3. Locations near the primary, considered in the non-uniform C<sub>2</sub>C demand evaluation methodology, are not included in the evaluation of DG capacity, because DG connections near the primary are likely to show very high levels of released DG capacity due to the relatively small impedance between the point of connection and the primary substation and the associated small voltage rise.
Each “pair” of DG connections (A2 and B2, or A3 and B3 as shown in Figure 28) is tested together. This is because Radial C2C operation requires a connection on each radial feeder to appropriately test the DG capacity which is released by the open ring circuit network; consequently, the same DG paired locations are tested for Interconnected C2C operation.

Point DG connections are made in addition to the DG connected for the DG base case. The capacity of each pair of DG connections is increased by the same factor until a thermal or voltage constraint occurs anywhere on the two feeders.
4.3 Demonstration of the effects of interconnection and C\(_2\)C operation on DG capacity using a simplified HV network

This section provides a simplified overview of the effects of C\(_2\)C operation on HV network DG capacity using hypothetical, but illustrative, simulated scenarios. The differences and subtleties between Radial C\(_2\)C and Interconnected C\(_2\)C operation, in terms of DG capacity released, are highlighted. This section follows the same process as conducted for demand capacity in Section 3.3.

4.3.1 Simplified HV network and assumptions

Figure 29 illustrates a simplified, but representative, HV network with the following properties:

- A simplified 11 kV network comprised of two feeders, with two secondary substations per feeder.
- A thermal rating of 5 MVA has been used for all branches.
- The maximum voltage permitted at any point in the HV network is 1.012 pu.
- Initially, a 500 kVA generator, with unity power factor, is connected at each secondary substation. This represents an arbitrary, nominal level of connected generation.
- Initially, all branches have the following positive sequence impedances: \(R = 0.1\) pu, \(X = 0.1\) pu (on a 100 MVA base). The branch associated with the NOP (if connected) has the same impedance as all other branches.
- No load is connected.

![Simplified HV network](image)

**Figure 29: Simplified HV network**

For simplicity, the examples given in this section do not include the effects of different branch thermal ratings, which is relevant in actual HV networks. The
relevant branch power flows and bus voltages are indicated on Figure 29 and throughout this section.

Three scenarios are considered with reference to the simplified HV network, as illustrated in Figure 30:

1. Symmetric feeder impedances and symmetric DG: both feeders are identical, i.e., have the same branch impedances and connected DG.
2. Asymmetric feeder impedances and symmetric DG: the impedances of the branches of feeder A are increased to: \( R = 0.5 \) pu, \( X = 0.5 \) pu; this emulates an increase in feeder length. The connected DG is identical. The NOP branch is shown as being longer in Figure 30, but it is not modelled as being longer.
3. Symmetric feeder impedances and asymmetric DG: the capacity of each of the generators connected to feeder A is doubled to 1 MVA. All branch lengths (i.e., impedances) are equal.

![Figure 30: Scenario circuit configurations](image)

4.3.2 Comparison of radial and interconnected operation under different scenarios

This section illustrates the effect of moving from radial to interconnected operation only, and describes the resulting effect on network power flows and bus voltages. The circuits are not at maximum loading, i.e., C2C operation has not been applied to the circuit.
4.3.2.1 Scenario 1 – Symmetric feeder impedances and symmetric DG

![Figure 31: Scenario 1 – radial (left) and interconnected (right)](image)

Due to symmetrical impedances and connected DG, closing the NOP has no effect; there is no power flow through the branch associated with the NOP, as shown in Figure 31.

4.3.2.2 Scenario 2 – Asymmetric feeder impedances and symmetric DG

![Figure 32: Scenario 2 – radial (left) and interconnected (right)](image)

For radial operation, the maximum voltage on feeder A is higher than scenario 1 due to the increased impedance: an increase from 1.001 pu to 1.007 pu at the extremity of the feeder. The voltage increases from the primary substation along the feeders due to the fact that power is being transferred from DG connected throughout the network to the primary substation (no load is connected).
For interconnected operation, a proportion of power generated on feeder A is supplied to feeder B (the electrically shorter feeder) via the NOP. Consequently, the power flows in feeder A are reduced compared to radial operation. The worst case secondary substation voltage is improved compared to radial operation, from 1.007 pu to 1.003 pu.

4.3.2.3 Scenario 3 – Symmetric feeder impedances and asymmetric DG

![Diagram of Scenario 3](image)

Figure 33: Scenario 3 – radial (left) and interconnected (right)

In this case, closing the NOP allows feeder B, which had less connected DG prior to interconnection, to export a proportion of the power generated on feeder A via the NOP.

4.3.3 Maximum capacity released under different scenarios for C₂C operation

This section assesses the maximum capacity released for each scenario, for both Radial C₂C and Interconnected C₂C configurations. All generators are scaled up in a uniform fashion until a thermal or voltage constraint occurs, as described in Section 4.2. In the following system diagrams, a red box around a branch’s power flow label or around a busbar voltage label illustrates the presence of a thermal or voltage constraint, respectively.
4.3.3.1 Scenario 1 – Symmetric feeder impedances and symmetric DG

Figure 34: Scenario 1 – Radial \( C_2C \) (left) and Interconnected \( C_2C \) (right)

Figure 10 shows the maximum DG capacities for Radial \( C_2C \) and Interconnected \( C_2C \) for the case that feeder impedances and the connected DG are symmetrical.

Closing the NOP has no effect on the maximum DG capacity of the ring circuit, which is 10 MVA in both Radial \( C_2C \) and Interconnected \( C_2C \) configurations, with the feeder section between the primary and the first secondary substation being thermally constrained in both cases.

4.3.3.2 Scenario 2 – Asymmetric feeder impedances and symmetric DG

Figure 35: Scenario 2 – Radial \( C_2C \) (left) and Interconnected \( C_2C \) (right)

When the impedance of feeder A is greater than that of feeder B, for Radial \( C_2C \) operation, feeder A experiences an over-voltage constraint at its extremity due to its...
higher impedance. The total DG capacity released by Radial C₂C operation is 3.2 MVA, which is significantly lower than for the theoretical maximum of 10 MVA for symmetric feeders (scenario 1).

For Interconnected C₂C operation, the asymmetry of the feeder impedances increases the power flow through feeder B and thereby “accelerates” the occurrence of a thermal constraint in the first branch of feeder B. However, Interconnected C₂C operation mitigates the voltage constraint at the extremity of feeder A. Therefore, the maximum DG demand released by Interconnected C₂C operation, 6.8 MVA, is significantly higher than the maximum DG capacity for Radial C₂C operation of 3.2 MVA. This is due to the methodology adopted for evaluating Radial C₂C operation, as described in Section 4.2.3, which defines the DG capacity as the value just before reinforcement is required on either of the radial feeders.

### 4.3.3.3 Scenario 3 – Symmetric feeder impedances and asymmetric DG

![Figure 36: Scenario 3 – Radial C₂C (left) and Interconnected C₂C (right)](image)

With the asymmetry in the DG, as shown in Figure 12, for Radial C₂C operation, the maximum DG capacity is limited by feeder A, which has a greater level of DG connected. Therefore the maximum Radial C₂C capacity is 7.5 MVA. Note that the thermal capacity of feeder B is relatively underutilised.

For Interconnected C₂C operation in this scenario, the total DG capacity is still limited by the first branch of feeder A. However, feeder B exports a proportion of the power generated on feeder A due to the impedances of the interconnected system. The maximum DG capacity released by Interconnected C₂C operation, 8.8 MVA, is therefore higher than for Radial C₂C for this scenario.

### 4.3.4 Overview of results for the simplified HV network

Table 1 summarises the maximum DG capacity released by Radial C₂C and Interconnected C₂C for each scenario, using the simplified HV network.
<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Feeder impedances</strong></td>
<td>Symmetric</td>
<td>Asymmetric</td>
<td>Symmetric</td>
</tr>
<tr>
<td><strong>DG arrangement</strong></td>
<td>Symmetric</td>
<td>Symmetric</td>
<td>Asymmetric</td>
</tr>
<tr>
<td><strong>Radial C₂C</strong></td>
<td>10 MVA</td>
<td>3.2 MVA</td>
<td>7.5 MVA</td>
</tr>
<tr>
<td><strong>Interconnected C₂C</strong></td>
<td>10 MVA</td>
<td>6.8 MVA</td>
<td>8.8 MVA</td>
</tr>
</tbody>
</table>

Table 3: Summary of maximum released DG capacity

The following can be concluded:

- If the two feeders comprising the ring circuit are perfectly symmetrical (scenario 1), which is highly unlikely in practice, there is no difference in the maximum DG capacity released by Radial C₂C or Interconnected C₂C; electrically, closing the NOP has no effect on DG capacity.
- If one of the feeders comprising the ring circuit has a higher impedance (scenario 2), or if one of the feeders comprising the ring circuit has more DG connected (scenario 3), Interconnected C₂C operation will cause a redistribution of power flows and a reduction in the maximum voltage rise – and will thereby generally release more DG capacity than Radial C₂C.

For simplicity, the effects of combinations of feeder impedance and DG asymmetry are not demonstrated in this section. However, in general, Interconnected C₂C operation results in a lower worst case voltage rise at secondary substations than Radial C₂C, because of the lower equivalent impedance between the primary and secondary substations. Therefore, unlike the simplified examples for demand capacity in Section 3.3, Interconnected C₂C is generally able to release more DG capacity than Radial C₂C because radial circuits are typically constrained by voltage rather than thermal capacity.
4.4 Results for ENWL C2C Trial Circuits

4.4.1 Uniform DG growth

Figure 37 illustrates the distributions of released DG capacity from the analysis of simulations of 36 C2C trial circuits, as percentage increases relative to the DG base case, using box plots for both Radial C2C and Interconnected C2C operation (see Section 3.4.1.1 for a description of how to interpret box plots). The mean values are labelled.

Figure 37: Summary of DG capacity released by C2C operation for uniform DG growth

The maximum DG capacity values, for a uniform growth in DG which can be connected before a constraint is encountered are presented in as a percentage increase in Figure 38 and in MVA in Figure 39. The types of constraints encountered are documented in Appendix B.

Figure 38: Maximum DG capacity values for uniform DG growth
The results demonstrate that C2C operation provides a significant increase in DG capacity compared to connections based on an N-1 planning approach – an average of approximately 175-225% assuming a uniform growth in DG (where 100% represents a doubling of DG capacity). The requirement for DG to remain connected during N-1 conditions for the DG base case limits the maximum DG capacity, and C2C operation thereby releases significant additional DG capacity.

Similarly to the demand capacity results described in Chapter 3, there is significant variability in the released DG capacity (40-400% for Radial C2C), which is dependent on the specific feeder impedances and DG locations. For example, for the “Griffin” circuit, which includes a relatively long overhead line spur, application of C2C operation releases up to approximately 0.33 MVA (67%) of additional DG capacity; a relatively short cable network such as the “Dickinson Street” circuit is able to release up to approximately 6 MVA (100%) of additional DG capacity.

On average, Interconnected C2C operation releases greater DG capacity (225%) than Radial C2C operation (175%). This is due to the fact that, for Radial C2C operation, a constraint on either radial feeder limits the capacity of both feeders as specified in Section 4.2.3. Furthermore, as illustrated in Section 4.3, Interconnected C2C operation generally benefits from lower voltage rises due to the lower equivalent impedance of the feeders. For example, the “Green Lane” circuit releases significantly more additional DG capacity for Interconnected C2C operation (235%) compared to Radial C2C operation (87%) because closing the NOP mitigates a voltage constraint at the extremity of one of the feeders.

In some cases, Radial C2C operation releases slightly more DG capacity than Interconnected C2C, such as for the “Chamber Hall” and “Crown Lane” circuits, as shown in Figure 38. This is because in these cases Interconnected C2C operation raises the voltage on one “side” of the NOP (compared to radial operation). The voltage increase at the NOP leads to a slight increase in the voltage at circuit extremities which are spurred from near the NOP. Consequently, less generation can be accommodated before the voltage reaches the upper voltage limit of 1.012 pu and the DG capacity for Interconnected C2C is less than that for Radial C2C. However, the difference in voltage at the NOP and the resulting difference in released DG capacity are relatively small.
Many of the scenarios shown in Figure 39 may require reinforcement of the primary transformers to accommodate the maximum theoretical C2C DG, especially if other circuits connected to the same primary substation were to accommodate similar levels of DG. For example, the “Middleton Junction” primary has a firm capacity of 23 MVA and Figure 39 illustrates that the circuits under study at Middleton Junction could export up to 11 MVA when maximum DG is connected. If other circuits connected to the same primary substation were to accommodate similar levels of DG, it is clear that the primary transformers may need upgraded to accommodate such growth.

4.4.2 Non-uniform DG growth

Figure 40 illustrates the maximum DG released for non-uniform (“point”) DG growth at specific circuit locations, alongside the results for uniform DG growth presented in Figure 37. On average, Interconnected C2C operation releases greater DG capacity than the corresponding Radial C2C scenarios.

On average, DG growth concentrated at locations near the NOP (A2 and B2 in Figure 40) results in slightly lower released DG capacity compared to uniform DG growth. However, there is also lower variation in the results across different circuits for locations A2 and B2 (approximately 90-260% for Radial C2C) compared to the distributions for uniform DG growth (approximately 40-400% for Radial C2C). This is because uniform DG growth includes some DG growth at circuit extremities and is therefore more sensitive to the topology of each circuit, thus leading to greater diversity of the results. The impedances between the NOP and the primary are relatively similar across the modelled circuits, therefore point DG growth near the

![Figure 40: DG capacity released by C2C operation](image)
NOP does not exhibit such a high sensitivity to circuit topology and the range of the results is narrower.

At the extremities of circuits, large DG connections are unlikely to be feasible due to voltage constraints caused by the relatively high impedance between the point of connection and the primary. This is illustrated by the results for locations A3 and B3 in Figure 40; on average, these locations release approximately half of the corresponding DG capacity released assuming uniform DG growth, for both Radial C2C and Interconnected C2C operation.
4.5 Conclusions

This chapter has described the methodology for evaluating the HV network DG capacity benefits of C2C and the results corresponding to the simulation of 36 C2C trial circuits. A DG base case has been established which represents the maximum DG that can be connected to a pair of radial HV circuits, without deploying C2C, i.e., assuming that DG must remain connected during N-1 conditions. The additional DG capacities, relative to the DG base case, which can be achieved by the deployment of Radial C2C operation and Interconnected C2C operation have been evaluated.

Two complementary methods of modelling additional, interruptible C2C DG capacity have been investigated:

1. Uniform DG growth, perhaps reflective of a high penetration of PV, which is relatively evenly distributed throughout existing secondary substations.
2. Non-uniform “point” DG, which may be reflective of relatively large localised generation such as a wind farm, CHP, or biomass.

From the results, the following can be concluded:

- As illustrated for C2C demand capacity in Chapter 3, C2C operation has the potential to accommodate a significant increase in DG connections on HV circuits, and therefore confirms the C2C project hypothesis that: “the C2C method will release significant capacity to customers from existing infrastructure”.
- For either Radial C2C or Interconnected C2C operation, the released DG capacity is highly dependent on the circuit topology and the relative modelled DG location.
- Interconnected C2C operation will typically release more DG capacity than Radial C2C operation, although there are exceptions to this.
- Assuming uniform growth in DG, Radial C2C operation can, on average, release 175% additional DG capacity; Interconnected C2C operation can release 225% additional DG capacity. If such extreme uptake of interruptible DG connections was to occur in HV circuits, and ignoring load connected to the circuit which would “negate” some of the exported power, other system factors such as primary transformer ratings may need to be considered.
- Assuming non-uniform DG growth, with point generators connected near the NOP location on each feeder, C2C operation is able to release significant DG capacity; however this would be lower than the DG capacity released by uniform DG growth for both Radial and Interconnected C2C operation.
- Assuming non-uniform DG growth, with point generators connected at the extremity of each feeder, significantly less DG capacity compared to uniform DG growth, for both Radial C2C and Interconnected C2C operation, can be released due to the higher impedances between the point DGs and the primary substations. However, even this evaluation of the additional DG at the circuit extremities facilitated by C2C operation still permits approximately a doubling of connected DG, compared to the DG base case, whether operating radially or interconnected.
For point DG connections relatively far from the primary, there is greater variation in the released capacity for each circuit compared to connections at (or near) the NOP. This is because the results depend on the topology of each circuit which varies significantly.
Chapter 5: Impact of C2C Operation on HV Network Technical Losses

5.1 Introduction

This chapter describes the methodology, results, and analysis for establishing the effects of C2C operation on electrical losses. In particular, this chapter answers the C2C project hypothesis: “the C2C method will reduce like-for-like power losses initially but this benefit will gradually erode as newly released capacity is utilised”.

The analysis distinguishes between the effects of demand-side response (DSR) and interconnected network operation, both of which affect losses. C2C operation is also compared to conventional reinforcement of HV radial networks, which would normally be required to connect the additional demand and DG connections facilitated by C2C. Only technical losses resulting from power dissipation in HV network conductors are analysed; transformer fixed losses and non-technical losses (e.g., from theft or metering inaccuracies) are not taken into consideration. The analysis process is summarised in Figure 41.

The methodology for defining the base case firm capacity, Radial C2C, and Interconnected C2C configurations is documented in Chapter 3. It is important to note that the results in this chapter relate to the losses incurred for the maximum demand which can be released by C2C operation and is therefore comparing the “at limit” scenario at a specific point in the future. This is different from the evaluation of losses being undertaken by the University of Manchester which determines cumulative losses over a continuous period of time into the future based upon a demand growth in accordance with a predetermined scenario.

Section 5.2 demonstrates the effects of interconnected operation on losses using simplified, but representative, simulated system scenarios. Section 5.3 describes the methodology for evaluating the effects of C2C operation on losses for Radial C2C operation, Interconnected C2C operation, and conventional reinforcement of radial networks. The full results for a selection of actual C2C trial circuits are presented in Section 5.4, and conclusions are drawn on these results in Section 5.5.
5.2 Effects of HV Network Interconnected Operation on Losses: Simplified Example

This section provides an overview of the theoretical impact that operating closed HV rings (as opposed to radial systems with open NOPs) may have upon HV network losses. A simplified example ring circuit is given in Figure 42. Its single-phase equivalent circuit is illustrated in Figure 43 (shown for scenario 1 defined below).

The effect of varying the impedance of feeder A or load A is provided in Table 4. The following can be concluded:

1. Closing the NOP for similar feeder and load impedances results in no change in losses. This is illustrated by scenario 1 in Table 4.
2. Closing the NOP for different feeder impedances, but similar load impedances, results in a minor reduction in losses. This is illustrated by scenarios 2 and 3 in Table 4.
3. Closing the NOP for similar feeder impedances, but different load impedances, results in a reduction in losses. This is illustrated by scenarios 4 and 5 in Table 4.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Feeder A</th>
<th>Feeder B</th>
<th>Load A</th>
<th>Load B</th>
<th>Total Losses NOP Open</th>
<th>Total Losses NOP Closed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 Ω</td>
<td>1 Ω</td>
<td>100 Ω</td>
<td>100 Ω</td>
<td>7.9 kW</td>
<td>7.9 kW</td>
</tr>
<tr>
<td>2</td>
<td>0.5 Ω</td>
<td>1 Ω</td>
<td>100 Ω</td>
<td>100 Ω</td>
<td>5.95 kW</td>
<td>5.35 kW</td>
</tr>
<tr>
<td>3</td>
<td>2 Ω</td>
<td>1 Ω</td>
<td>100 Ω</td>
<td>100 Ω</td>
<td>11.7 kW</td>
<td>10.5 kW</td>
</tr>
<tr>
<td>4</td>
<td>1 Ω</td>
<td>1 Ω</td>
<td>20 Ω</td>
<td>100 Ω</td>
<td>95.4 kW</td>
<td>69.8 kW</td>
</tr>
<tr>
<td>5</td>
<td>1 Ω</td>
<td>1 Ω</td>
<td>500 Ω</td>
<td>100 Ω</td>
<td>4.12 kW</td>
<td>2.93 kW</td>
</tr>
</tbody>
</table>

Table 4: Effect on per-phase losses for varying feeder A and load A impedances (green indicates a reduction)

The following assumptions apply to this simplified example:
• All loads are at the end of the feeders, which is representative of the worst case scenario for losses, assuming radial operation. In practice, loads are distributed along the feeders.
• For simplicity, reactive impedances are not considered.
• The switch representing the NOP has a resistance of 0.1 Ω when closed, to represent the additional feeder impedance. The losses resulting from this resistance are included in Table 4.
• Constant-resistance loads are assumed, but results leading to similar conclusions can be obtained with constant power loads in a simulation package such as IPSA. The sensitivity of the losses results to load type is discussed in detail in Appendix D.
5.3 Methodology for Evaluating C\(_2\)C Losses

5.3.1 Overview of methodology

The annual losses for C\(_2\)C network operation, for the 36 C\(_2\)C trial circuits, are evaluated using the following process:

1. Simulate peak losses

2. Estimate annual losses for Radial C\(_2\)C and Interconnected C\(_2\)C operation

3. Estimate annual losses for equivalent conventionally-reinforced networks

1. Simulation of the peak losses for each of the 36 modelled C\(_2\)C trial circuits. To determine the worst case losses for C\(_2\)C operation, the maximum demand released by C\(_2\)C operation for each circuit is considered in this chapter. Uniform demand growth, as described in Chapter 3, has been considered in this evaluation of losses. The maximum demands released by Radial C\(_2\)C and Interconnected C\(_2\)C operation, for a given circuit, are different; to allow for a fair comparison, “maximum C\(_2\)C demand” is defined as the lower of these released demands. Losses are always calculated for system intact conditions.

2. Estimate annual losses for Radial C\(_2\)C and Interconnected C\(_2\)C operation, using the simulated peak losses and historical demand data. This is described in Sections 5.3.2, 5.3.3, and 5.3.4.

3. Estimation of the annual losses in a reinforced radial system supplying the “maximum C\(_2\)C demand”. I.e., for a fair comparison with C\(_2\)C losses, the system is considered to be reinforced to support at least the same level of demand as C\(_2\)C. This is described in Section 5.3.5.

5.3.2 Use of historical demand data

The historical system demand is available in the form of half-hourly averaged RMS current measurements at the primary substations from all 72 trial radial feeders (i.e., each pair of feeders per 36 ring circuits) for the year 2012 (from 1\(^{st}\) January 2012 to 31\(^{st}\) December 2012). Figure 44 presents an indicative, simplified circuit layout with the demand measurement locations shown. The mean and peak loading data can be extracted for each of the 72 radial feeders and therefore it is possible to estimate the mean and peak loads for the 36 ring circuits. The load factor (LF) and loss load factor (LLF) can be calculated for each radial feeder and for each ring circuit. The annual losses for each circuit can subsequently be estimated from the peak losses determined in circuit simulations [3], [4].
The LF and LLF values for each circuit can be calculated as follows:

\[
LF = \frac{\text{mean demand}}{\text{peak demand}}
\]

\[
LLF = k \times LF + (1 - k) \times LF^2, \quad \text{where } k = 0.2
\]

The actual annual losses can be estimated using simulation data as follows:

\[
\text{Annual losses (kWh)} = \text{losses at peak demand (kW)} \times 24 \times 365 \times LLF
\]

It should be noted that this approach is based on empirical evidence, assuming normal system operation.

It has been assumed that the half-hourly current measurements were all recorded with the 72 feeders operating radially (with the NOP open). To estimate the demand values for the 36 ring circuits (with the NOP closed), the individual current half-hourly data have been aggregated for each pair of feeders that form each ring circuit. This assumes that closing the NOP and forming a ring does not incur any changes in demand.

A single set of mean demand, peak demand, LF, and LLF values is calculated for each ring circuit. The same LLF value is used for calculating annual losses for all configurations of each circuit, whether operating radially or interconnected. It is therefore assumed that the calculated LLF is valid for these configurations, and remains valid as the ring circuit loading is linearly scaled\(^6\). This can be considered to be pessimistic for the evaluation of losses in an interconnected system, because it

\(^6\) Therefore, it is assumed that both the mean and peak demand for each circuit increase proportionately (i.e., their ratio is constant), resulting in constant values for the LF and LLF under all loading conditions and circuit configurations.
does not make allowance for possible diversity between the demands on the two radial circuits (see Section 3.4.3 for a discussion of demand diversity).

5.3.3 Processing of historical demand data

Before aggregation of the feeder demand data (as described in Section 5.3.2) and further analysis of losses, it is critical to remove or replace all significantly spurious data points in the feeder current measurements. Even a single erroneous value, such as a measured value “frozen” at a large value such as 700 A, would severely distort calculated values for the circuit peak current. This process has been carried out carefully to avoid, for example, interpolating weekdays using weekends; the interpolation catered for daily, weekly, and seasonal trends. Interpolating from other spurious data points has also been avoided. It is not possible to simply use a moving average when determining the peak demand, because there are several instances of consecutive spurious data. The process also avoids discarding actual anomalies in the demand behaviour.

Figure 45 summarises the process of importing and processing the feeder demand data and further detail is presented in Appendix C.

5.3.4 Calculated LLF values and annual losses

Table 5 provides the results for the 36 modelled ring circuits after applying the processing methodology described in Section 5.3.3.
### Table 5: Output from demand measurement processing

<table>
<thead>
<tr>
<th>Primary Substation</th>
<th>Nominal Voltage (kV)</th>
<th>Calculated Ring Peak Current (A)</th>
<th>Calculated Ring Mean Current (A)</th>
<th>Load Factor</th>
<th>Loss Load Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashton on Mersey</td>
<td>6.6</td>
<td>366</td>
<td>182</td>
<td>0.50</td>
<td>0.30</td>
</tr>
<tr>
<td>Castleton</td>
<td>6.6</td>
<td>394</td>
<td>185</td>
<td>0.47</td>
<td>0.27</td>
</tr>
<tr>
<td>Chamber Hall</td>
<td>6.6</td>
<td>314</td>
<td>165</td>
<td>0.53</td>
<td>0.33</td>
</tr>
<tr>
<td>Chassen Road</td>
<td>6.6</td>
<td>323</td>
<td>163</td>
<td>0.51</td>
<td>0.31</td>
</tr>
<tr>
<td>Chatsworth St</td>
<td>11</td>
<td>406</td>
<td>210</td>
<td>0.52</td>
<td>0.32</td>
</tr>
<tr>
<td>Clover Hill</td>
<td>6.6</td>
<td>294</td>
<td>156</td>
<td>0.53</td>
<td>0.33</td>
</tr>
<tr>
<td>Crown Lane</td>
<td>11</td>
<td>470</td>
<td>244</td>
<td>0.52</td>
<td>0.32</td>
</tr>
<tr>
<td>Denton East</td>
<td>6.6</td>
<td>308</td>
<td>149</td>
<td>0.48</td>
<td>0.28</td>
</tr>
<tr>
<td>Dickinson Street</td>
<td>6.6</td>
<td>317</td>
<td>161</td>
<td>0.51</td>
<td>0.31</td>
</tr>
<tr>
<td>Droylsden East</td>
<td>6.6</td>
<td>337</td>
<td>187</td>
<td>0.56</td>
<td>0.36</td>
</tr>
<tr>
<td>Exchange St</td>
<td>6.6</td>
<td>406</td>
<td>217</td>
<td>0.53</td>
<td>0.34</td>
</tr>
<tr>
<td>Farnworth</td>
<td>11</td>
<td>314</td>
<td>165</td>
<td>0.53</td>
<td>0.33</td>
</tr>
<tr>
<td>Great Harwood</td>
<td>6.6</td>
<td>336</td>
<td>182</td>
<td>0.54</td>
<td>0.34</td>
</tr>
<tr>
<td>Green Ln</td>
<td>11</td>
<td>255</td>
<td>127</td>
<td>0.50</td>
<td>0.30</td>
</tr>
<tr>
<td>Greenhill</td>
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<td>308</td>
<td>141</td>
<td>0.46</td>
<td>0.26</td>
</tr>
<tr>
<td>Griffin</td>
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<td>352</td>
<td>176</td>
<td>0.50</td>
<td>0.30</td>
</tr>
<tr>
<td>Heywood</td>
<td>6.6</td>
<td>470</td>
<td>244</td>
<td>0.52</td>
<td>0.32</td>
</tr>
<tr>
<td>Higher Mill</td>
<td>6.6</td>
<td>431</td>
<td>224</td>
<td>0.52</td>
<td>0.32</td>
</tr>
<tr>
<td>Holme Rd</td>
<td>11</td>
<td>364</td>
<td>190</td>
<td>0.52</td>
<td>0.32</td>
</tr>
<tr>
<td>Hyde</td>
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<td>312</td>
<td>151</td>
<td>0.49</td>
<td>0.29</td>
</tr>
<tr>
<td>Hyndburn Road</td>
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<td>336</td>
<td>182</td>
<td>0.54</td>
<td>0.34</td>
</tr>
<tr>
<td>Levenshulme</td>
<td>6.6</td>
<td>247</td>
<td>127</td>
<td>0.51</td>
<td>0.31</td>
</tr>
<tr>
<td>Levenshulme 2</td>
<td>6.6</td>
<td>560</td>
<td>293</td>
<td>0.52</td>
<td>0.32</td>
</tr>
<tr>
<td>Middleton Junction</td>
<td>11</td>
<td>308</td>
<td>141</td>
<td>0.46</td>
<td>0.26</td>
</tr>
<tr>
<td>Monton</td>
<td>6.6</td>
<td>317</td>
<td>161</td>
<td>0.51</td>
<td>0.31</td>
</tr>
<tr>
<td>Moss Nook</td>
<td>11</td>
<td>323</td>
<td>163</td>
<td>0.51</td>
<td>0.31</td>
</tr>
<tr>
<td>Musgrave</td>
<td>6.6</td>
<td>277</td>
<td>135</td>
<td>0.49</td>
<td>0.29</td>
</tr>
<tr>
<td>Reddish Vale</td>
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<td>460</td>
<td>229</td>
<td>0.50</td>
<td>0.30</td>
</tr>
<tr>
<td>Roman Rd</td>
<td>6.6</td>
<td>352</td>
<td>176</td>
<td>0.50</td>
<td>0.30</td>
</tr>
<tr>
<td>Royton</td>
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<td>497</td>
<td>218</td>
<td>0.44</td>
<td>0.24</td>
</tr>
<tr>
<td>Sale</td>
<td>6.6</td>
<td>346</td>
<td>195</td>
<td>0.56</td>
<td>0.37</td>
</tr>
<tr>
<td>South East Macc 22</td>
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<td>372</td>
<td>178</td>
<td>0.48</td>
<td>0.28</td>
</tr>
<tr>
<td>Spa Road</td>
<td>6.6</td>
<td>408</td>
<td>205</td>
<td>0.50</td>
<td>0.30</td>
</tr>
<tr>
<td>St Annes</td>
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<td>294</td>
<td>156</td>
<td>0.53</td>
<td>0.33</td>
</tr>
<tr>
<td>Whalley Range</td>
<td>6.6</td>
<td>346</td>
<td>195</td>
<td>0.56</td>
<td>0.37</td>
</tr>
<tr>
<td>Woodley</td>
<td>11</td>
<td>372</td>
<td>178</td>
<td>0.48</td>
<td>0.28</td>
</tr>
</tbody>
</table>

#### 5.3.5 HV network reinforcement

##### 5.3.5.1 Overview of potential approaches

For a fair comparison of losses, the losses for alternative systems must be evaluated for the same level of demand. The chosen level is the “maximum C2C demand”, but this could not be supported by the existing system and so reinforcement is required. There are numerous forms of HV network reinforcement, as listed below, with the final choice being based on engineering judgement.

1. Install additional backfeeds
Create additional interconnections, with NOPs, to other circuits. These provide additional backfeeds for load transfers during N-1 conditions. This approach will have little or no impact on losses during system intact conditions and therefore does not present a realistic alternative for comparison with the losses for C2C operation.

2. Install a duplicate circuit

Add a new circuit from the primary to the location of the new connection. The new circuit may be “breached” onto an existing feeder to avoid the cost of adding another primary circuit breaker. In principle, this approach can, at best, halve circuit losses in the reinforced section, for the same level of demand. However, this approach is difficult to automate within a simulation and apply to all the modelled C2C trial circuits because it involves making informed decisions about where to connect new circuits; an automated version may make arbitrary and unrealistic decisions.

3. Reinforce by circuit overlays

Overlay existing cables or lines with new cable. In general, this is not a common approach for major reinforcement at HV. The original assets are permanently disconnected, and cables are typically left in the ground rather than being removed. Typically, 300 mm$^2$ aluminium (ACAS) with a cyclic rating of 400 A [5] is used by ENWL to overlay HV circuits. This approach is only advantageous if the rating of the original circuit section is lower than the rating of the overlay; the maximum demand which can be supported by the replacement circuit (which is dictated by N-1 configurations, and ignores any backfeeds from other circuits) will be limited by the rating of the cable used for the reinforcement. Initial simulation studies have determined that an automated reinforcement process based on overlay is not able to match the maximum level of capacity released by C2C operation in the majority of cases. Voltage constraints are generally not considered by ENWL planning engineers when assessing new demand connections; instead reinforcement may be considered if operational issues occur, such as customers experiencing voltages outside of the regulatory limits.

The above issues mean that it is very difficult to capture the genuine HV reinforcement practice in a realistic and generic manner suitable for simulation-based analyses. In general, each circuit would require a bespoke arrangement for reinforcement depending on the circumstances. Because none of the above approaches are appropriate, a different approach is required and this is described in the following section.

5.3.5.2 Proposed reinforcement approach

A simplified approach has been used to estimate losses within the reinforced HV network. This approach assumes that reinforcement is undertaken in a manner that, on average, maintains constant losses (as a percentage of demand) as demand increases beyond the base case firm capacity. In reality, connections and reinforcement would occur on a discrete basis over time, and therefore the
relationship between demand and losses would not be constant. However, this approach provides a simple and consistent method for comparing losses in a system with $C_2C$ to those in a conventionally-reinforced system.
5.4 Results and Analysis

5.4.1 Effect of interconnected operation

Figure 46 provides an impression of the effect of Interconnected C2C operation on annual losses as demand increases (i.e., due to load growth over time) for all 36 ring circuits. Simulated losses are expressed as a percentage of demand, which leads to a linear relationship between demand and losses. It is assumed that as demand reaches the base case firm capacity, Interconnected C2C operation is “enabled”: all additional loads are interruptible and the NOP is closed. In 35 out of 36 cases, the change in system configuration leads to an immediate reduction in losses, however in some cases the change is marginal. Closing the NOP to provide two parallel paths to supply the load current has been shown to reduce losses in the simplified example presented in Section 2. The mean reduction in peak instantaneous losses at base case firm capacity is 8% across all modelled ring circuits, with the individual reductions ranging from -7% to 46% (of the original losses value). As would be expected, 11 kV circuits generally experience lower losses than 6.6 kV circuits for the similar levels of transmitted power, due to the lower load current for a given power value.

![Figure 46: Variation in annual losses, by voltage level, after enabling Interconnected C2C operation](image)

Figure 47 emphasises the effect of closing the NOP on losses using box plots, for connected demand which equals the base case firm capacity (i.e., no interruptible C2C is connected). On average, interconnected operation alone, without DSR, provides a reduction in losses of 0.07% (0.70% minus 0.63%) as a percentage of demand.
5.4.2 Trends in losses

It is important to compare losses for C\textsubscript{2}C operation to the equivalent losses that would be incurred under the assumed reinforcement process applied to radial networks. The individual trends in losses for each circuit are given in detail in Figure 48. The plots should be interpreted as follows:

- The red and green curves plot the trajectories of annual losses (for the entire ring circuit) for Radial C\textsubscript{2}C and Interconnected C\textsubscript{2}C operation respectively.
- The orange curves plot the trajectories of annual losses (for the entire ring circuit) for conventional radial operation with the assumed reinforcement approach. In all cases, these trends are “flat” because the losses (as a percentage of demand) are assumed to be constant as demand grows beyond the base case firm capacity.
- The green shaded areas indicate the improvement in capacity offered by Interconnected C\textsubscript{2}C operation after the base case firm capacity has been reached. For simplicity, the equivalent regions for Radial C\textsubscript{2}C are not shown.
- Solid grey vertical lines at the boundaries of shaded areas indicate thermal constraints; dashed vertical lines indicate voltage constraints.
Figure 48: Ring circuit losses, capacity, reinforcement, and constraints
Figure 49 compares the distributions of the results given in Figure 48 as box plots, for the losses corresponding to Radial C\textsubscript{2}C and Interconnected C\textsubscript{2}C operation for each circuit, alongside the losses for the reinforced circuit\textsuperscript{7}. The mean values for each distribution are labelled (and happen to coincide with the median values which are shown as vertical lines inside the coloured boxes). For each circuit, losses for Radial C\textsubscript{2}C, Interconnected C\textsubscript{2}C, and reinforcement are compared at the same level of demand (the “maximum C\textsubscript{2}C demand” as defined in Section 5.3.1).

Figure 49: Comparison of losses for each circuit configuration at maximum C\textsubscript{2}C demand

With reference to Figure 48 and Figure 49, the following can be noted:

- For approximately half of the 36 modelled circuits, the gradient of the increase in losses is approximately equal for both Radial C\textsubscript{2}C and Interconnected C\textsubscript{2}C operation. As noted in Section 5.2, this indicates similar losses for Radial C\textsubscript{2}C and Interconnected C\textsubscript{2}C configuration and that many circuits are relatively “balanced” in terms of feeder impedances, load locations, and load ratings. It also shows that the NOP locations have been selected to generally balance power flows and minimise losses for radial network operation.
- For the other circuits, the gradient of the increase in losses, as demand is increased, is generally greater for Radial C\textsubscript{2}C than for Interconnected C\textsubscript{2}C because of the benefit of lower circuit impedance due to the parallel paths for load current when the NOP is closed. On average, at the maximum level of demand released by C\textsubscript{2}C operation, this leads to a marginal reduction in average losses from 1.06% for Radial C\textsubscript{2}C to 0.97% for Interconnected C\textsubscript{2}C.
- As shown in Figure 49, on average, radial reinforcement leads to a reduction in annual losses of approximately 0.3% compared to C\textsubscript{2}C operation.

\textsuperscript{7} The losses values for reinforcement are the same as for “Base case firm capacity (radial)” given in Figure 47.
• The benefit of reduced losses due to closing the NOP is diminished as demand increases because of the “missed” opportunity for reduced losses which is typically provided by conventional reinforcement.
• The “Chamber Hall” circuit experiences slightly higher losses for Interconnected C2C operation, compared to Radial C2C operation, due to additional losses associated with the power flow through the interconnecting circuit at the NOP.
5.5 Conclusions

This chapter has quantified the effects of C2C operation on HV network losses. In particular, annual losses have been evaluated for the maximum level of demand released by C2C operation. The losses arising from Radial C2C operation and Interconnected C2C operation have been compared with losses in conventionally-reinforced radial networks.

The following changes in losses resulting from C2C operation can be expected:

1. Losses remain unchanged, relative to radial operation with reinforcement, until demand grows to the base case firm capacity and C2C operation is applied.
2. Losses may be reduced if the NOP is closed, i.e., if Interconnected C2C operation is adopted rather than Radial C2C operation. In some cases, the reduction is marginal because the locations of NOPs are already optimised to minimise losses for conventional radial HV network operation.
3. As interruptible “C2C” demand grows, losses for C2C operation will increase relative to radial operation with reinforcement.
4. At the maximum levels of demand released by C2C, C2C operation leads to annual HV network losses of approximately 1%, as a percentage of demand. This is approximately 0.3% higher than the equivalent losses assumed from conventional reinforcement of the radial networks.

On average, at maximum C2C demand, there is a marginal reduction in losses of approximately 0.09% for Interconnected C2C operation as opposed to Radial C2C operation.

Therefore, the C2C hypothesis that “the C2C method will reduce like-for-like power losses initially but this benefit will gradually erode as newly released capacity is utilised”, can be validated in two parts:

1. The reduction in losses that is gained through closing the NOP for Interconnected C2C operation. For example, closing the NOP for the base case firm capacity results in an average decrease in peak instantaneous losses of 8%.
2. As demand increases, facilitated by C2C operation and the consequent avoidance of reinforcement, there is clearly a proportional increase in losses.
Chapter 6: Impact of C$_2$C Operation on Power Quality

6.1 Introduction

This chapter describes the methodology, results, and analysis of the study for evaluating the impact of C$_2$C operation on power quality. In particular, this chapter investigates the C$_2$C project hypothesis: “the C$_2$C method will improve power quality resulting from stronger electrical networks”. This is achieved using theoretical HV circuit examples and through detailed analysis of power quality monitoring data gathered during the C$_2$C trial.

Using power quality monitoring data, several measured system parameters are compared to ascertain any differences that are apparent as a result of operating in either Radial C$_2$C mode or Interconnected C$_2$C mode during the C$_2$C trial. Therefore, the effects of C$_2$C operation on power quality – if any – can be quantified. The analysis focuses on quantifying the effects of interconnected operation (as opposed to radial operation) on RMS voltage, voltage harmonics, and flicker. This process is summarised in Figure 50. Effects on power quality due to additional demand or generation accommodated by C$_2$C operation are not included in the analysis.

Figure 50: Overview of power quality analysis process

Section 6.2 provides a simplified overview of the effects of C$_2$C on HV network power quality using hypothetical, but illustrative, simulated scenarios. Section 6.3 describes the methodology used to analyse the measured power quality monitoring data from the monitored circuits, with further details provided in Appendix G. The full results for a selection of actual C$_2$C trial circuits are presented in Section 6.4, and conclusions are drawn on these results in Section 6.6.
6.2 Theoretical impact of C₂C operation on voltage harmonic distortion using a representative HV network

6.2.1 Overview

This section provides an overview of the theoretical effects of C₂C operation – i.e., using interconnected HV ring circuits as opposed to radial circuits – on HV network voltage harmonics. This is examined in three parts:

1. The background theory and modelling approach are described in Section 6.2.2.
2. The potential for C₂C operation to affect voltage harmonic distortion is discussed in Section 6.2.3. Specific examples are given which illustrate the main relevant effects of C₂C operation on voltage harmonic distortion. The modelling and results are not related to a specific C₂C trial circuit.
3. Generic patterns, which could be extrapolated for a large number of HV networks, are determined using the Monte Carlo method, as described in Section 6.2.4.

6.2.2 Simplified HV modelling

6.2.2.1 Overview of THD

The results in this section are given as the voltage total harmonic distortion (THD) at the HV side of primary and secondary substations for various scenarios. THD is used to quantify the cumulative effects of all harmonics measured at a particular location. Equation 1 provides a definition of THD [6]:

\[
THD = \sqrt{\frac{\text{sum of squares of amplitudes of all harmonics}}{\text{amplitude of fundamental}}} \times 100\%
\]

Equation 1: Definition of THD

The use of the term “THD” in this chapter refers to voltage THD. The THD calculations include the 2nd to 50th harmonic integer multiples.

6.2.2.2 HV system

A simplified HV ring circuit representation, as illustrated in Figure 51, has been simulated using MATLAB Simulink and SimPowerSystems [7]. The equivalent electrical representation of the circuit shown in Figure 51 is presented in Figure 52, with harmonic injection locations identified. The upstream equivalent system is approximated by modelling it as an 11 kV ideal voltage source with a source reactance of 0.484 Ω at 50 Hz [8] (equivalent to a fault level of 250 MVA) and an assumed X/R ratio of 5. The parameters used are specified in Appendix F.1.
Figure 51: Simplified HV system

Figure 52: HV system equivalent circuit
ENWL HV systems are typically resistance-earthed, and secondary distribution transformers typically use a delta-star configuration. Both of these factors will tend to reduce or block the propagation of zero-sequence (i.e., triplen: 3rd, 6th, 9th, etc.) harmonics. For this reason, triplen harmonics have been excluded from the analysis. The analysis could therefore be applicable to real ENWL HV systems. Therefore, because no triplen harmonics are analysed, the earthing resistance, $R_N$ shown in Figure 52 never comes into effect.

6.2.2.3 Modelling harmonic injection

Harmonic injection has been modelled using constant current sources. The frequency, magnitude, and phase of current harmonics can be specified precisely and therefore arbitrary harmonic profiles can be defined for each harmonic injection location. As noted in [6], the use of constant current sources is sufficiently accurate for scenarios which do not involve unrealistically high voltage THD (>10%).

Harmonic injection can be applied at the primary substation busbar to emulate “background” THD which is caused by, for example, harmonic current associated with load or generation connected to other HV feeders or connected to the upstream system. The harmonic injections at secondary substations, $HIA$ and $HIB$, are approximations because harmonic injections would be distributed.

6.2.3 Theoretical effects of $C_2C$ operation on THD

6.2.3.1 Theoretical discussion

A common rule of thumb is that “an increase in fault level leads to a decrease in voltage harmonic distortion”. While in some contexts this rule is true, it must be considered carefully in the context of each particular network, and its relevance to $C_2C$ operation must be clarified. The change in voltage harmonic distortion depends on what has caused the fault level increase and on the resulting configuration of harmonic injection on the system. To illustrate this, the calculated voltage harmonic distortion, $v_h$, resulting from a single equivalent downstream harmonic injection current, $I_h$, can be calculated as a percentage of the supply voltage, $V_s$ [9]:

$$v_h = I_h Z_h \frac{\sqrt{3} \times 100}{V_s} \%$$

Equation 2: Calculated voltage distortion

where $Z_h$ is the upstream system impedance\(^8\) for harmonic number $h$. Typically, the system harmonic impedance can be calculated as:

$$Z_h = h Z_1 = h \frac{V_s^2}{F}$$

where $Z_1$ is the fundamental system impedance and $F$ is the short-circuit fault level. Therefore, $v_h$ can be estimated in terms of the fault level:

\(^8\) The factor $k$ discussed in [9] has been ignored for simplicity. The resistance of $Z_h$ is also ignored.
Equation 3: Calculated voltage distortion as a function of fault level, $F$

$$v_h = \frac{I_h h \times \sqrt{3} V_s \times 100}{F} \%$$

If the downstream harmonic injection equivalents do not change, the voltage harmonic distortion reduces for an increase in fault level.

For C$_2$C operation, which involves interconnecting two radial HV feeders to create a closed ring, there is potential for both the fault level and the harmonic injection at the location of interest to change; i.e., two variables in Equation 3 change: $F$ and $I_h$. The fault level will increase due to the lower effective system impedance, and the harmonic injection will also change because harmonic currents injected on either feeder could partly “pollute” the other feeder. Harmonic currents of the same frequency may add (if in phase) or may cancel-out (if in anti-phase); i.e., the resulting voltage distortion depends on the vector sum of current harmonics at each frequency.

Therefore, it is possible that C$_2$C operation could either decrease or increase THD, depending on the change in $I_h$. Sections 6.2.3.2 and 6.2.4 estimate the likely extent of the overall change in THD due to C$_2$C operation.

6.2.3.2 Harmonic injection examples

Table 6 summarises four examples which quantify the effects of C$_2$C operation on THD when there is no background harmonic distortion$^9$. For each harmonic injection location, two harmonic frequencies have been selected: 5$^{\text{th}}$ (a relatively low non-triplen) and 23$^{\text{rd}}$ (a relatively high non-triplen). “$\delta THD$” is the change in THD due to C$_2$C operation (i.e., THD for interconnected operation minus that for radial operation). Changes from the base example are highlighted in blue. A reduction in THD is highlighted in green, and an increase in THD is highlighted in red.

---

$^9$ The impact of background harmonic distortion is discussed in Appendix F.2.
The following effects on THD due C₂C operation can be observed:

- Even for secondary substations relatively far from the primary, as considered in Figure 51, the change in THD due to C₂C operation is likely to be relatively small. Therefore, even for cases where C₂C increases THD at secondary substations, THD is likely to remain within planning limits providing that some existing margin is available.
- If the two feeders are “symmetrical” – i.e., the various parameters are equal – there is no change in THD at secondary substations.
- If feeder A experiences higher harmonic current injection than feeder B, the THD at secondary substations on feeder A will decrease (and increase on feeder B) due to interconnected operation.
- If feeder A has higher impedance than feeder B, the THD at secondary substations on feeder A will decrease (and increase on feeder B) due to interconnected operation.
- The THD contribution from each feeder can combine or cancel out depending on the phases of the harmonic current.
- The THD at the primary substation will not be affected by closing the NOP (except for a slight influence due to background harmonics, as discussed in Appendix F.2). Furthermore, secondary substations which are relatively close to the primary substation will experience a lesser change in THD compared with more distant secondary substations. However, it is possible for voltage harmonics caused by harmonic injection at a secondary substation to cancel-out (or add to) background voltage harmonics at the primary; however, C₂C operation will not significantly affect this.
• If the NOP branch length is not ignored, the THD in Example 3 will still be reduced at both secondary substations A and B, but will not be fully eliminated due to the impedance (and the resulting harmonic phase difference) between the two substations.

6.2.4 Monte Carlo simulations

6.2.4.1 Overview

The HV system in Figure 51, although simplified, offers several variables which can potentially affect voltage THD:

1. Feeder lengths and the resulting impedances.
2. The length and impedance of the circuit section associated with the NOP.
3. The location of harmonic injection, such as: at the primary substation (due to causes not related to the simulated ring circuit), secondary substations, or at LV. However, modelling harmonic injection at LV does not make a significant difference to the results of $\delta THD$ at HV or LV (although absolute THD values are higher at LV than at HV due to the additional impedance). Therefore, LV harmonic injection is not included in the simulations.
4. The amount of harmonic injection at each location, which is comprised of several harmonic numbers (frequencies) with associated magnitudes and phases.
5. The rating, power factor, and location of load and generation on the ring circuit.

To characterise the generic behaviour of C2C operation on THD, the Monte Carlo method has been used to simulate a wide variety of possible inputs. Three scenarios have been simulated:

1. No fixed variables; all variables are included as random inputs. The nature of harmonic currents is dictated by the specific device or technology which connects to the system and causes the harmonic injection. Although diversity in the phase angles of injected harmonics (leading to cancellation, reducing THD) is possible [10], the worst-case (where harmonics accumulate, increasing THD) should be considered [9]. Therefore, the harmonic numbers and phases selected for $Hl_A$ are also used for $Hl_B$. However, the impact of this consideration is relatively small, and only leads to a very slight “widening” of the distribution shown in Figure 53. The harmonic injection at the primary, $Hl_p$, is varied independently. No triplen harmonics are used.
2. As for Scenario 1, except harmonic injection is fixed: the magnitudes of harmonics $Hl_A$ are fixed at twice the magnitudes of the $Hl_B$ harmonics.
3. As for Scenario 1, except feeder lengths (i.e., impedances) are fixed: Feeder A = 4 km, Feeder B = 2 km.

The full list of variables used in the Monte Carlo simulations is given in Appendix F.3.

6.2.4.2 Results
Figure 53 illustrates the distributions of $\delta THD$ for secondary substations A and B for Scenario 1. The distributions are centred very close to zero (as shown from the median values in Table 7) which indicates that, on average, the change in THD due to C$_2$C operation is negligible. Furthermore, the maximum change in THD is relatively small; the 5$^{th}$ percentile value is approximately -0.14%.

![Figure 53: Distributions of $\delta THD$ with no fixed variables – Scenario 1](image)

Figure 54 and Figure 55 illustrate the effects of asymmetry between the two feeders comprising the ring circuit. Feeders which tend to have a higher proportion of harmonic injection (Feeder A in Figure 54) or a higher proportion of the total feeder impedance (Feeder A in Figure 55), tend to experience a reduction in THD due to C$_2$C operation. Conversely, the other feeder will tend to experience an increase in THD. However, as shown in Table 7, on average there is near-zero impact on THD.
Figure 54: Distributions of $\delta THD$ with fixed harmonics – Scenario 2

Figure 55: Distributions of $\delta THD$ with fixed feeder lengths – Scenario 3

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1: no fixed variables</th>
<th>Scenario 2: fixed harmonics</th>
<th>Scenario 3: fixed feeder lengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location A median $\delta THD$</td>
<td>0.000560%</td>
<td>-0.04443%</td>
<td>-0.05950%</td>
</tr>
<tr>
<td>Location B median $\delta THD$</td>
<td>-0.000302%</td>
<td>0.03906%</td>
<td>0.03205%</td>
</tr>
</tbody>
</table>

Table 7: Summary of median Monte Carlo simulation results

6.2.5 Summary of simulation results
The main conclusions from the theoretical evaluation of voltage harmonic distortion are:

- On average, interconnected operation will not affect voltage THD at primary substations, secondary substations, or at LV.
- In general, if the two feeders comprising a ring circuit exhibit asymmetry in their impedances or harmonic injection, interconnected operation will decrease THD on one feeder and increase THD the other feeder (with no net change in THD at the primary substation). This is analogous to the effect of interconnected operation on the steady-state fundamental RMS voltage.
- For the cases where interconnected operation does change voltage THD, the impact is relatively small and THD is likely to remain within system planning limits (4% at HV [9]) provided there is some existing margin.
6.3 Methodology for power quality analysis

6.3.1 Overview of monitoring regime

“PQube” power quality monitoring devices [11] have been installed within 77 secondary substations throughout 36 C-C trial ring circuits, with at least two PQube devices located per ring circuit (i.e., at least one PQube per radial feeder which are interconnected to form a ring). Figure 56 highlights representative power quality monitoring locations which have been used in the analyses. All PQube devices are connected at LV within a substation relatively close to the NOP. During the C-C trial, the NOP for each ring circuit has been periodically opened or closed such that measurements have been made for both Radial C-C and Interconnected C-C modes of operation, with at least seven days of data from each mode of operation, to capture an acceptable range of loading conditions, being required for analysis.

Monitoring data are stored on Secure Digital (SD) flash memory cards which must be manually collected from each monitoring location periodically. The monitoring data are stored in comma-separated values (CSV) files on the SD cards collected from the PQube devices, with separate files for:

- Monthly trends (5-minute sampling),
- Weekly trends (5-minute sampling),
- Daily trends (1-minute sampling), and
- Detailed harmonics data: up to the 63rd harmonic with inter-harmonics, per-phase for voltage and current (15-minute sampling period).

A PQube device is shown in Figure 57.
6.3.2 Overview of data validation

It is critical to validate the monitoring data so that any conclusions being drawn from the measurements are sound and fair. In particular, it is important that the internal clock of each PQube is relatively accurate (within a few minutes of a known, absolute time reference such as UTC) and reliable. This is because comparisons must be made between radial and interconnected network configurations; this involves aligning monitoring data to independently time-stamped switching events from ENWL control room logs. The following steps are performed to validate the monitoring data (with the full details described in Appendix F):

1. Merge and convert all PQube data into a suitable format for analysis.
2. Determine the data availability profile for each monitoring location, i.e., the dates where the PQube was operational and correctly recorded data.
3. Validate clock synchronisation of all PQube devices using a measured frequency trend correlation technique developed for this analysis.
4. Where possible, correct and align clocks and measurement data which exhibit a time offset.
5. Show that there is a correlation between the individual phases of the measured data, to provide confidence that the data represent valid system measurements.

6.3.3 Monitoring data used for numerical analysis

For each monitoring location, the following relevant data are available from the PQube device, which measures waveform quantities and calculates the associated power quality parameters according to the appropriate international standards:
- Individual phase RMS currents.
- Individual phase RMS voltages.
- Total Harmonic Distortion (THD, as defined in IEEE Std 519 [12]), per-phase.
- Total Demand Distortion (TDD, as defined in IEEE Std 519 [12]), per-phase.
- Short term flicker (Pst, as defined in IEC 61000-4-15 [13]), per-phase.
- Long term flicker (Plt, as defined in IEC 61000-4-15 [13]), per-phase.

For simplicity and to reduce the computational requirements, 5-minute data samples have been used in the numerical analysis rather than 1-minute samples. It is assumed that the extra granularity from using 1-minute sampling would make no difference to the analysis, especially for flicker which is updated over 10 minute or 2 hour intervals in the PQube calculations and according to standards [13].

### 6.3.4 Analysis method

To analyse the effects, if any, of interconnected operation on power quality, a log of NOP statuses has been examined for occurrences of NOP state changes. “Valid” events are extracted where the state of the NOP is consistent for one week before and one week after the NOP state change. It is assumed that week-by-week demand is similar, and therefore that the relevant power quality metrics can be compared fairly for Radial C2C and Interconnected C2C operation. Following the initial validation process described in Appendix G and analysis of the NOP state change log, Table 8 lists the number of valid events.

<table>
<thead>
<tr>
<th>Number of valid events</th>
<th>Number of monitoring locations included</th>
<th>Number of ring circuits included</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>49</td>
<td>31</td>
</tr>
</tbody>
</table>

Table 8: Summary of valid events after initial validation

Typical results for an NOP state change event are illustrated in Figure 58. The 95\(^{th}\) percentile values for each plot are shown as horizontal dashed lines. It can be observed that, in this case, the assumption that the week-by-week demand is very similar is true. However, note that Figure 58 provides three-phase averages, but the numerical analysis considers each phase individually. The vertical dashed line shows the moment of interconnection, i.e., the closing of the NOP.
Figure 58: Example of PQube monitoring results for an NOP state change
The data from all valid events are used to numerically analyse the difference between Radial C2C and Interconnected C2C operation. The analysis method involves the following steps:

1. Elimination of monitoring locations for NOP state change events where the mean difference in demand between the two weeks to be compared is greater than 5%. This threshold has been chosen by examining the distribution of the differences in mean demand between the two weeks on either side of the NOP state change; in the majority of cases, the difference in demand is within 5%. Table 9 lists the total number of valid events. 28 events were excluded from the analysis due to mean differences in demand between the two weeks being greater than 5%; however, this represents a statistically significant sample size of valid events.

<table>
<thead>
<tr>
<th>Number of valid events</th>
<th>Number of monitoring locations included</th>
<th>Number of ring circuits included</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>34</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 9: Summary of valid events after demand validation

2. Extraction of the per-phase monitoring data for each valid monitoring location. Each phase is treated independently in the analysis. Clearly there will be a mixture of three-phase and single-phase loads connected at each secondary substation, but it is assumed that the results can be analysed on a per-phase basis. In Section G.6, the correlations between the per-phase measurements are tested to evaluate the credibility of the data.

3. Quantification of the extent of the change, if any, for each power quality metric, as described in Section 6.4.
6.4 Results and quantification of impact on power quality for ENWL C2C trial circuits

As described in Section 6.3.4, weekly monitoring data for Radial C2C and Interconnected C2C operation are compared. Figure 59 plots distributions of the difference in mean weekly measurements. For example, the mean difference in THD, $\delta \text{THD}$, is calculated as:

$$\delta \text{THD} = \text{Mean THD (Interconnected C2C)} - \text{Mean THD (Radial C2C)}$$

Therefore, a $\delta \text{THD}$ positive value represents generally higher THD for Interconnected C2C operation compared with Radial C2C operation. For simplicity, the results for each phase – which are calculated individually – are combined in the distributions given in Figure 59.

The following subsections discuss the results for each measurement type.
Figure 59: Comparison of change in measurements (Interconnected C2C “minus” Radial C2C)
6.4.1 Demand

Figure 59 illustrates that the distribution of the difference in mean demand is centred on 0.0 A, and is not significantly skewed to either side. The maximum difference in mean demand is approximately ±15 A; this is to be expected because the events with significant difference in the mean demand (> 5%) have been excluded from the analysis. Therefore, it can be concluded that the difference in demand for each selected event is less than 5% and it will not significantly affect other measurements, particularly RMS voltage.

6.4.2 RMS voltage

The distribution of $\delta V$ in Figure 59 is not skewed to either side indicating that there is no overall increase or reduction in the RMS voltage due to switching from Radial C$_2$C to Interconnected C$_2$C operation, i.e., the event does not tend to affect voltage in any direction and the random variation has a normal distribution centred around zero. Most of the values are with ±1.0 V, where the nominal value is approximately 240 V.

Therefore, the results indicate that closing the NOP has negligible effect on RMS voltage. Furthermore, the impact of closing the NOP is likely to be insignificant compared with other factors which affect the daily variation in voltage due to normal system operation, such as variation in demand (on all feeders connected to the same primary) and primary transformer tap changes.

The additional demand and DG connections which can be accommodated by C$_2$C operation in the future will affect the HV network voltage. However, the methodologies presented in Chapter 3 and Chapter 4 do not permit demand of generation penetrations which result in a voltage constraint. Therefore, even for the theoretical maximum levels of demand or DG due to C$_2$C operation, steady-state HV voltages will not be in violation of planning limits (i.e., below 0.94 pu or above 1.012 pu).

6.4.3 Impact on harmonics (THD and TDD)

Figure 59 illustrates that there are slight differences in THD when comparing Radial C$_2$C and Interconnected C$_2$C operation. The distribution slightly tends towards an increase in THD for Interconnected C$_2$C compared to Radial C$_2$C operation. However, the maximum increase is only approximately 0.5%. Figure 60 presents mean THD measurements for each valid week period, for both Radial C$_2$C and Interconnected C$_2$C. Similar to Figure 59, the results for the individual phases have been combined in Figure 60. At less than 3%, the maximum measured THD is well within the UK planning level of 5% for LV circuits [9].
The results in Figure 59 for TDD do not show any significant skew around zero and therefore do not indicate significant change in LV current harmonics between Radial C2C and Interconnected C2C operation. This result confirms that the change in voltage THD is not associated with a change in harmonic current.

The additional demand and DG connections which can be accommodated by C2C operation in the future may affect voltage harmonics. However, this depends significantly on the type of load, particularly whether or not the connections are converter-interfaced.

6.4.4 Impact on flicker (short term Pst and long term Plt)

It can be observed in Figure 59 that the distributions of $\delta Pst$ and $\delta Plt$ are tightly centred on the value of 0.0, indicating that there is generally very little change in flicker when switching from Radial C2C to Interconnected C2C operation. Overall, there is a slight negative bias indicating a reduction in Pst and Plt for Interconnected C2C operation.
6.5 Relation of monitoring data to simulation models

The monitoring data analysis presented in Section 6.4.3 exhibits a slight skew towards higher $\delta THD$ on average. However, the Monte Carlo simulations in Section 6.2.4 predict that the distribution of $\delta THD$ is likely to be centred around zero on average. As shown in Section 6.2.4.2, asymmetry between the feeders, due to either differences in feeder length or harmonic injection, can affect $\delta THD$.

The discrepancy in $\delta THD$ from the monitoring data can be explained by examining the locations of each monitoring device associated with each valid NOP state change event and testing for asymmetry in the feeder demands (which is assumed to be proportional to harmonic injection) and length.

Table 10 summarises the results. Locations are weighted appropriately if they are included for multiple valid monitoring events.

- There is a slight tendency for feeders with power quality monitoring to experience lower demand, which may indicate lower harmonic injection. As shown for Scenario 3 in Section 6.2.4.2, this tends to increase $\delta THD$.
- There is a very slight tendency for feeders with power quality monitoring to have longer impedance. As shown for Scenario 2 in Section 6.2.4.2, this theoretically tends to decrease $\delta THD$. However, the difference shown in Table 10 is very close to zero and therefore the effect is likely to be negligible.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Mean asymmetry</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean primary feeder current measurements</td>
<td>-10.7 A</td>
<td>A negative value means that on average the monitored feeders experienced lower demand than their counterpart. A negative value shows bias towards increased THD when interconnected.</td>
</tr>
<tr>
<td>(from 2012 demand data)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean feeder impedance difference (from IPSA</td>
<td>0.0297 $\Omega$</td>
<td>A negative value means that on average the monitored feeders were shorter or of lower impedance than their counterpart. A negative value shows bias towards increased THD when interconnected.</td>
</tr>
<tr>
<td>models)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 10: Mean monitoring location data
6.6 Conclusions

This chapter has described the methodology and results for evaluating the effects of C2C operation, in particular interconnected operation, on power quality. Power quality measurements from 77 secondary substations throughout the ENWL network and over the course of the C2C trial have been analysed to compare the effects of Radial C2C operation and Interconnected C2C operation. Extensive validation of the monitoring data has been performed to ensure that the data are valid and that the comparisons are sound. A statistically significant sample size of valid events has been used in the analysis.

There is no evidence that Interconnected C2C operation improves or is detrimental to the RMS voltage profile at LV when compared with Radial C2C operation.

On average, Interconnected C2C operation does not significantly affect voltage THD, although there is some evidence that voltage THD may marginally increase. However, the measurement data indicate that the worst case mean THD measured at LV, approximately 3%, is well within the planning level of 5% [9]. This result has been confirmed through theoretical analysis.

There is evidence that both short term flicker (Pst) and long term flicker (Plt) are slightly reduced for Interconnected C2C operation when compared to Radial C2C operation.

C2C operation permits significant future increases in connected demand and DG, which could affect power quality. However, the demand and DG capacity studies require that HV network voltages remain within planning limits. The impact of additional demand and DG on voltage harmonics is dependent on the type of load and the type of connection.

The results are valid for the power quality experienced for LV-connected customers. However, HV monitoring is necessary to precisely determine the impact of Interconnected C2C operation on HV customers.

In conclusion, the results show that Interconnected C2C operation is likely to have only a marginal impact on power quality at HV and LV, and this therefore the hypothesis that “the C2C method will improve power quality resulting from stronger electrical networks” is only true under certain circumstances.
Chapter 7: Impact of C₂C Operation on HV Fault Levels

7.1 Introduction

This chapter describes the methodology, results, and analysis for evaluating the impact of C₂C operation on ENWL HV network fault levels. It is important that the impact of C₂C operation on fault levels is understood to ensure that ENWL HV network equipment is not at risk due to excessive fault levels, i.e., that fault levels at primary substations, HV customers, and ring main units (RMUs) remain within circuit breaker and equipment withstand ratings. It is also important to determine if fault levels are likely to limit the deployment of C₂C operation in the future.

The methodology caters for the inclusion of motor loads, which are part of the general connected demand and contribute to fault currents, and for distributed generation (DG). This report examines the worst case fault levels and therefore includes the maximum possible demand and DG connections for C₂C operation, as determined in Chapter 3 and Chapter 4. The results focus on the fault levels at the primary and at the NOP, which experience the greatest increases in fault level due to C₂C operation. The analysis process is summarised in Figure 61.

![Figure 61: Overview of fault level analysis process](image)

Section 7.2 describes the modelling and methodology used from determining the increase in fault levels due to C₂C operation. The full results for a selection of actual C₂C trial circuits are presented in Section 7.3, and conclusions are drawn on these results in Section 7.5.
7.2 Fault level modelling methodology

7.2.1 Overview of methodology

Models suitable for fault level studies have been created for 36 modelled trial ring circuits and these study results have been analysed to determine the effects of C2C operation on fault levels. There are three causes of fault level increase due to C2C operation:

1. Fault-contributing demand growth (due to motors);
2. DG growth; and
3. Network interconnection leading to reduced fault path impedance.

A representation of the modelled fault infeeds and fault locations for an HV ring circuit is given in Figure 62. The equivalent fault current infeed from the general load connected across the ring is modelled "lumped" at the primary substation, which is an approximation based on the guidance in Engineering Recommendation G74 [14]. This is described in further detail in Section 7.2.3. Fault levels are calculated assuming a uniform growth in DG and therefore DG connections are distributed throughout the circuits as described in Chapter 4. The DG fault current infeed is described in detail in Section 7.2.4. The fault levels at each "side" of the NOP are different (especially for radial operation with the NOP in the open position) and therefore both NOP fault locations are considered in the methodology, in addition to primary HV busbar faults.

The fault levels for the scenarios listed in Table 11 have been investigated. Therefore, the increase in fault level due to C2C operation, i.e., the difference between Radial C2C (or Interconnected C2C) and the appropriate base case, can be quantified. This approach separates the impact of the individual causes of the
increase in fault level. It is assumed that the demand base case and the DG base case represent the maximum fault level contributions from demand and DG, respectively, for conventional (non-C\textsubscript{2}C) operation as established in Chapter 3 and Chapter 4. Scenarios 1c, 2c, and 3c include the connection of both the maximum C\textsubscript{2}C demand and DG which have been evaluated separately. The impact on power flows, voltage constraints, and thermal constraints is ignored for the simulation of fault levels.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Demand connected?</th>
<th>DG connected?</th>
<th>C\textsubscript{2}C operation?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Demand base case</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>1b</td>
<td>Maximum C\textsubscript{2}C demand</td>
<td>Yes</td>
<td>No</td>
<td>Radial C\textsubscript{2}C</td>
</tr>
<tr>
<td>1c</td>
<td>Maximum C\textsubscript{2}C demand</td>
<td>Yes</td>
<td>No</td>
<td>Interconnected C\textsubscript{2}C</td>
</tr>
<tr>
<td>2a</td>
<td>DG base case</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>2b</td>
<td>Maximum C\textsubscript{2}C DG</td>
<td>No</td>
<td>Yes</td>
<td>Radial C\textsubscript{2}C</td>
</tr>
<tr>
<td>2c</td>
<td>Maximum C\textsubscript{2}C DG</td>
<td>No</td>
<td>Yes</td>
<td>Interconnected C\textsubscript{2}C</td>
</tr>
<tr>
<td>3a</td>
<td>Demand and DG base case</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>3b</td>
<td>Maximum C\textsubscript{2}C demand and DG</td>
<td>Yes</td>
<td>Yes</td>
<td>Radial C\textsubscript{2}C</td>
</tr>
<tr>
<td>3c</td>
<td>Maximum C\textsubscript{2}C demand and DG</td>
<td>Yes</td>
<td>Yes</td>
<td>Interconnected C\textsubscript{2}C</td>
</tr>
</tbody>
</table>

Table 11: Summary of investigated fault level scenarios

7.2.2 Upstream HV network modelling

The system design fault level for 11 kV and 6.6 kV systems is 250 MVA, as defined in ENWL Code of Practice documentation [8]. The fault level results for C\textsubscript{2}C operation are expressed as a percentage increase of the design fault level (250 MVA), relative to the appropriate base case\textsuperscript{10}. The use of the 250 MVA design rating avoids the variability associated with actual circuit breaker ratings for each primary substation.

The modelled fault level contribution from the upstream equivalent network – without any additional demand or DG connected, and assuming radial operation – is:

- Approximately 60% of the design fault level at the primary substation, which is representative of typical HV fault levels as specified in ENWL’s Long Term Development Statement (LTDS) [15] (which ranges between 53% and 69% for the 36 modelled circuits);

- Approximately 10-50% of the design fault level at the NOP, depending on the impedance of each feeder.

Therefore, the base fault level at the Primary HV busbar is modelled in IPSA using an equivalent three-phase Grid Infeed component of 150 MVA (i.e., 60% of the 250 MVA for each transformer)\textsuperscript{10}.

\textsuperscript{10} For example, an increase of 25 MVA (e.g., from 150 MVA to 175 MVA) would be a 10% increase.
MVA design level). An X/R ratio of 5 is assumed. Although the actual fault level and X/R ratio will differ for each circuit and will vary over time, this provides a consistent base for comparison.

Positive-sequence conductor impedances values are specified within the C2C IPSA simulation models, and these values have been derived from conductor data sheets [5], [16].

7.2.3 Demand fault contribution modelling

It is assumed that part of the general load simulated in the C2C IPSA models includes induction machines which can contribute to fault levels [14], [17]. For C2C operation, additional fault level contribution must be modelled to cater for the additional demand facilitated by C2C. Engineering Recommendation G74 [14] provides guidance on modelling the impact of these motor loads by assuming an initial symmetrical fault level contribution of 1 MVA per 1 MVA of general load connected at 33 kV, and assuming an X/R ratio of 2.76. However, the approaches used in [6] and [15] assume that this approach can also be applied at 11 kV or 6.6 kV primary busbars. Therefore, the equivalent general load fault level contribution corresponding to the total load on both feeders will be modelled at the 11 kV or 6.6 kV primary busbar of the ring circuit of interest, as shown in Figure 62. The C2C IPSA simulation models only include the two feeders which constitute one ring circuit; the potential G74 infeed from other feeders connected to the same primary substation is not included.

This approach assumes that the upstream system (such as primary transformer ratings) does not limit the downstream C2C interruptible demand capacity. Therefore, this assumes the worst case in terms of fault level contributions.

Table 12 provides the base induction machine parameters used for the calculation of the results in [15]. These parameters are used to model the equivalent general load fault contribution at the primary busbar in the C2C IPSA simulations. The impedance values are to be scaled down proportionately to the rating of the demand; e.g., a doubling of the required demand rating requires a halving of the impedance values. The induction machine parameters are calculated and applied in a Python script because the use of the IPSA database feature cannot be scripted.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Per unit values, per-MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model type</td>
<td>Standard induction machine, with rotor impedances “inner-outer”</td>
</tr>
<tr>
<td>Magnetising reactance</td>
<td>20.87 pu</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>0.0894 pu</td>
</tr>
<tr>
<td>Stator reactance</td>
<td>0.6707 pu</td>
</tr>
<tr>
<td>Inner rotor resistance</td>
<td>0.2496 pu</td>
</tr>
<tr>
<td>Inner rotor reactance</td>
<td>0.2684 pu</td>
</tr>
</tbody>
</table>

Table 12: Induction machine parameters, per-MVA, for G74 infeed

7.2.4 DG fault contribution modelling
DG is modelled as a synchronous machine which is directly-connected at HV at secondary substations, with an RMS fault current contribution at the machine’s terminals of 4 times its rated current; this is a pessimistic assumption (compared to, for example, converter-interfaced DG [18]) and is representative of the worst case fault contribution from DG. The potential DG infeed from other feeders connected to the same primary substation as the circuits being analysed is not included. However this is offset by the pessimistic assumption that all modelled DG has a relatively high fault current contribution.

It is assumed that the DG is connected to the HV network via a transformer; the equivalent DG model should account for the transformer impedance and X/R ratio. In order for the equivalent DG model to supply a fault current of 4 times the DG rated current, ignoring its armature resistance, an equivalent reactance of 0.25 pu should be selected, as shown in Figure 63.

![Figure 63: Required DG equivalent HV reactance](image)

However, an appropriate equivalent resistance and X/R ratio must be selected. A typical 500 kVA transformer has an X/R ratio of 4 and an impedance of 0.04 pu on rating [19]. Assuming that the transformer that will be considered for the DG model has a similar X/R ratio of 4, but a reactance of 0.04 pu, its resistance is assumed to be 0.01 pu. These transformer impedances are summarised in Figure 64.

![Figure 64: DG transformer impedances](image)

Ignoring the DG armature resistance, the only resistance considered for the equivalent DG model will be 0.01 pu, which can be regarded as its armature resistance. The overall impedance will be the sum of the DG impedance and the transformer impedance because these two components are connected in series. Consequently, the DG model will comprise an overall reactance of 0.25 pu and an armature resistance of 0.01 pu, thus leading to an X/R ratio of 25. The combined DG and transformer impedances are shown in Figure 65, which meets the required equivalent reactance specified in Figure 63. Fault level studies require specification of the DG sub-transient, transient, and synchronous reactances (and the corresponding time constants) and the armature resistance. For simplicity, it is assumed that $X'_{d} = X''_{d} = X_{d}$, i.e., the symmetrical component of the fault current contribution is constant over time.
The per unit parameters to be used in IPSA to model the equivalent DG are specified in Table 13. The impedance values are to be scaled down proportionately with the required rating of the DG; e.g., a doubling of the DG rating requires a halving of the impedance values. For a 1 MVA DG connected at 6.6 kV (with a rated current of 87.5 A), the peak make fault current is 931 A and the RMS break fault current is 349 A.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Per unit values, per-MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-transient reactance ((X_{d}^{''}))</td>
<td>0.25 pu</td>
</tr>
<tr>
<td>Transient reactance ((X_{d}^{'})</td>
<td>0.25 pu</td>
</tr>
<tr>
<td>Synchronous reactance ((X_{d}))</td>
<td>0.25 pu</td>
</tr>
<tr>
<td>Synchronous or armature resistance ((R_{a}))</td>
<td>0.01 pu</td>
</tr>
</tbody>
</table>

Table 13: DG synchronous machine parameters, per-MVA

A unity power factor has been assumed for all fault level studies involving DG. As noted in reference [17], the selection of DG power factor will affect the fault current contribution from the DG. However, the difference in fault current contribution is relatively small (approximately +7% of the DG RMS break contribution for a 0.95 lagging power factor) compared with the assumption that DG supplies fault currents of 4 times its rated current.

### 7.2.5 Fault types

Three-phase short-circuit faults are applied at locations indicated in Figure 62 for the 36 C2C IPSA simulation models. A fault impedance of 0 Ω is applied to determine the worst case fault current. Analysis of single-phase faults is excluded because ENWL 11 kV and 6.6 kV systems are impedance-earthed so that single-phase fault currents are significantly less than phase-phase and three-phase fault currents.

For each fault location, the fault current at the point of fault is recorded. Specifically, the results are recorded as “peak make” and “RMS break” fault current values, which is consistent with ENWL documentation [15], which also complies with Engineering Recommendation G74 [14]. The “peak make” value is defined as the peak asymmetrical current within the first cycle of fault occurrence (normally at 10 ms after inception). The “RMS break” value is defined as the symmetrical fault current 100 ms after fault occurrence. The processes for simulating faults and recording results are
performed automatically by software. A factor of 2.5, which is the specified ratio of rated peak withstand current and rated short-time withstand current [20], is used to normalise the simulated peak make values for comparison with the RMS design fault level value of 250 MVA.

Table 14 summarises the fault types under investigation and the corresponding IPSA parameters, where the RMS symmetrical component of the fault current is $i_{ac}$ and the asymmetrical component is $i_{dc}$. This method has been verified with the results provided in [15] and using ENWL’s Grid and Primary (G&P) IPSA model.

<table>
<thead>
<tr>
<th>Fault type</th>
<th>Fault current value</th>
<th>Fault setting in IPSA</th>
<th>Fault time in IPSA</th>
<th>Values from IPSA fault level results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-phase</td>
<td>Peak make</td>
<td>Peak</td>
<td>10 ms</td>
<td>Peak asymmetrical fault current (\text{equivalent to } \sqrt{2i_{ac} + i_{dc}})</td>
</tr>
<tr>
<td>Three-phase</td>
<td>RMS break</td>
<td>Symmetric RMS</td>
<td>100 ms</td>
<td>RMS symmetrical fault current (i.e., i_{ac})</td>
</tr>
</tbody>
</table>

Table 14: Summary of fault types and IPSA parameters
7.3 Results and quantification of impact on fault levels for ENWL C2C trial circuits

7.3.1 Increase in fault levels at primary substations

Figure 66 and Figure 67 illustrate the simulated increase in RMS break and peak make fault levels, respectively, at the primary substation for different configurations: maximum C2C demand capacity; maximum C2C DG capacity; and both maximum C2C demand and DG capacity. The increases – illustrated as box plots – are calculated relative to the corresponding base case, as listed in Table 11. The impact of Radial C2C vs. Interconnected C2C operation can be compared. The 95th percentile values for each distribution are highlighted in the figures because these are indicative of the worst case fault level increases, but excluding the most extreme outliers in the data. The mean values are also labelled, where appropriate.

Figure 66: RMS break fault level increase at primary substations relative to corresponding base case
7.3.2 Increase in fault levels at the NOP

Similarly to the results in Section 7.3.1, Figure 68 and Figure 69 illustrate the simulated increase in RMS break and peak make fault level, respectively, at the NOP. Fault locations on both “sides” of the NOP are included in the results to ensure that the worst case results are captured (i.e., there are 72 NOP fault level results for the 36 modelled circuits).
Figure 68: RMS break fault level increase at the NOP relative to corresponding base case

Figure 69: Peak make fault level increase at the NOP relative to corresponding base case
7.3.3 Summary of maximum fault level increase

Table 15 summarises the maximum likely fault level increases at primary substations due to C\textsubscript{2}C operation given in the box plots in Section 7.3.1 and Section 7.3.2. The contribution from each source of fault current – demand, DG, and interconnected operation\textsuperscript{11} – is specified. Similarly, Table 16 summaries the maximum fault level increases at the NOP. At most, C\textsubscript{2}C operation can lead to a total increase in fault levels of 12.4\% of the design rating at primaries or 22.2\% at the NOP.

<table>
<thead>
<tr>
<th>Source of Fault Current</th>
<th>RMS Break</th>
<th>Peak Make</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial C\textsubscript{2}C demand</td>
<td>0.1%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Radial C\textsubscript{2}C DG</td>
<td>10.2%</td>
<td>10.3%</td>
</tr>
<tr>
<td>Radial C\textsubscript{2}C demand + DG</td>
<td>10.2%</td>
<td>11.1%</td>
</tr>
<tr>
<td>Interconnected C\textsubscript{2}C demand + DG</td>
<td>11.9%</td>
<td>12.4%</td>
</tr>
<tr>
<td>Effect of interconnected operation (approximate)</td>
<td>1.7%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Maximum</td>
<td>11.9%</td>
<td>12.4%</td>
</tr>
</tbody>
</table>

Table 15: Maximum increase in fault level, relative to design rating, at primary

<table>
<thead>
<tr>
<th>Source of Fault Current</th>
<th>RMS Break</th>
<th>Peak Make</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial C\textsubscript{2}C demand</td>
<td>0.0%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Radial C\textsubscript{2}C DG</td>
<td>6.6%</td>
<td>5.1%</td>
</tr>
<tr>
<td>Radial C\textsubscript{2}C demand + DG</td>
<td>6.6%</td>
<td>5.1%</td>
</tr>
<tr>
<td>Interconnected C\textsubscript{2}C demand + DG</td>
<td>22.1%</td>
<td>22.2%</td>
</tr>
<tr>
<td>Effect of interconnected operation (approximate)</td>
<td>15.5%</td>
<td>17.1%</td>
</tr>
<tr>
<td>Maximum</td>
<td>22.1%</td>
<td>22.2%</td>
</tr>
</tbody>
</table>

Table 16: Maximum increase in fault level, relative to design rating, at NOP

\textsuperscript{11} The results for the effect of interconnected operation are estimated from the difference between the 95\textsuperscript{th} percentile values for the demand + DG cases given in Figure 66 and Figure 67. For example, from Figure 66, 11.9\% - 10.2\% = 1.7\%, as given in Table 12. However, it should be noted that the individual fault level contributions from each source of fault level increase cannot be added together directly because they are vector quantities.
7.4 Analysis of results and impact on the ENWL system

The impact of additional demand released by C2C on fault levels is relatively small, whether considering fault levels at the primary or the NOP. The G74 fault current contribution decays relatively quickly and therefore has very little impact on RMS break current levels. Furthermore, because the G74 infeed is modelled lumped at the primary substation, the impedance of the circuit between the primary and the NOP does not allow for a significant increase in fault levels at the NOP (or for other circuit locations which are electrically far from the primary substation).

The fault level results at the primary are dominated by the additional fault level contribution from DG which can be released by C2C operation. It can be observed that Interconnected C2C operation with DG tends to lead to slightly higher percentage increase of fault levels at the primary (12.4%), compared with Radial C2C (10.3%), due to the DG fault current contribution travelling via two possible paths; i.e., there is lower impedance between the DG and the primary for Interconnected C2C operation. Furthermore, Interconnected C2C operation generally releases more DG capacity than Radial C2C. DG is modelled as distributed uniformly on the ring circuit, and therefore the fault level results depend on the topology of the circuits and their impedances. As a consequence, the C2C DG fault level results vary more greatly compared with results for C2C demand fault level contribution, which is lumped at the primary.

Interconnected C2C operation has a moderate impact on fault levels at the NOP compared with Radial C2C. However, the feeder impedances limit fault currents (depending on the location of the fault current infeed) for faults at the NOP and therefore the overall fault level at these locations is lower than at the primary by an average of 19.9 MVA (8% of the design fault level).

For the 36 modelled circuits, the maximum fault level with either Radial C2C or Interconnected C2C operation is within the design fault level at any circuit location (the worst case is 202 MVA, or 81% of the design fault level). Using the circuit breaker peak make and RMS break ratings given in the ENWL 2014 LTDS [15], on average, C2C operation reduces the peak make headroom by 4-5% and the RMS break headroom by 3-4% (as a percentage of circuit breaker rating). Furthermore, for all 374 ENWL primary substations documented in [15], 99% could accommodate the maximum theoretical increase in fault level at the primary of 12% of the design rating.
7.5 Conclusions

This chapter has described the methodology and results for the effects of C2C operation on ENWL HV fault levels. The methodology has been designed to cater for the worst case conditions to evaluate the maximum theoretical increase in fault levels. Therefore, the maximum demand capacity and DG capacity which can be released by C2C operation have been included in the fault level analysis. The results focus on fault levels at primary substations and at NOPs, which experience the greatest increase in fault levels due to C2C operation.

At most, C2C operation on one HV ring circuit adds approximately 11.9% of the design rating to primary fault levels, and a maximum of 22.1% at the NOP. This includes the increase due to additional demand, additional DG, and interconnected operation. Interconnected C2C operation contributes approximately an additional 1-2% of the design fault level to primary fault levels and 15-17% at the NOP. For all modelled circuits, fault levels remain within design levels and this is representative of the majority of ENWL HV circuits.

At locations relatively close to the NOP, the increase in fault level is significantly higher for Interconnected C2C, as opposed to Radial C2C, due to the lower short-circuit impedance resulting from the two parallel paths for fault current. However, the overall fault level at these locations is lower than at the primary substation due to the impedance of the feeders.

The addition of DG is the most significant factor contributing to the increase in fault levels, and this depends on the DG capacity released by C2C for each circuit (which, for some circuits, is high relative to the primary transformer ratings). Note that the results only include the growth in DG from the two modelled feeders per primary substation whereas there are likely to be several other feeders connected to the same primary which may also experience growth in connected DG. However this is offset by the pessimistic assumption that all modelled DG has a relatively high fault current contribution; it is likely that a significant proportion of DG will be converter-interfaced with a lower fault current contribution.

It can be concluded that the additional fault level contribution associated with C2C operation moderately increases fault levels, but fault levels should be expected to remain within the design fault level for HV networks. It can also be concluded that fault levels are unlikely to be the greatest constraint on C2C adoption in the future; it is more likely that circuit thermal or voltage constraints, or primary transformer ratings, will limit the demand or DG capacity released by C2C operation, rather than C2C connections being limited by excessive fault levels.
Chapter 8: Key Conclusions and Learning Outcomes

8.1 Overview of results

This report has presented an analysis of various aspects associated with the technical performance of C2C operation. In particular, this report has established the impact of increased HV network interconnection and demand-side response (DSR) on: demand capacity, DG capacity, HV network technical losses, power quality, and fault levels.

The simulation studies of actual C2C trial circuits have shown that C2C operation can release significant demand and DG capacity, compared to the defined base case scenarios. Specifically, the capacity released by C2C has been compared with an assessment of the maximum demand or DG which can be accommodated by conventional operation (i.e., non-C2C, which requires that demand and DG remain connected during N-1 conditions) without requiring reinforcement. On average, C2C operation can achieve up to approximately a 76% increase in demand and a 225% increase in DG capacity. However, the results depend significantly on the individual circuit topologies, the ratings of circuit sections, and load or DG locations. On average, Interconnected C2C operation releases more demand and DG capacity compared with Radial C2C operation.

The technical losses arising from C2C operation have been compared with losses in a reinforced radial system. Losses are typically reduced for closed-ring HV network operation, i.e., if Interconnected C2C operation is adopted rather than Radial C2C operation. In some cases, the reduction is marginal because the locations of NOPs are already optimised to minimise losses for conventional radial HV network operation. At the maximum levels of demand released by C2C, C2C operation leads to annual HV network losses of approximately 1%, as a percentage of demand. At maximum C2C capacity, this is approximately 0.3% higher than the equivalent losses assuming conventional reinforcement of the radial networks (0.7%, as a percentage of demand). Furthermore, maximum C2C capacity levels may never be met in the future, so this maximum increase in losses may never be encountered.

Power quality measurements from 77 secondary substations throughout the C2C trial network area spanning a significant period of the duration of the C2C trial have been analysed to compare the effects of Radial C2C operation and Interconnected C2C operation. Extensive validation of the monitoring data has been performed to ensure that the comparisons are sound. There is no evidence that Interconnected C2C operation is detrimental to the RMS voltage profile at LV when compared with Radial C2C operation. There is some evidence that voltage THD increases marginally for Interconnected C2C operation. However, the measurement data indicate that the worst case mean THD measured at LV, approximately 3%, is well within the planning level of 5%. There is evidence that both short term flicker (Pst) and long term flicker (Plt) are slightly reduced for Interconnected C2C operation when compared to Radial C2C operation.
It has been demonstrated that C2C operation – even at the most extreme levels of released demand and DG on one HV ring circuit – is unlikely to exceed HV design fault level ratings or restrict the future adoption of C2C.

8.2 Validation of C2C project hypotheses

The work described in this report validates the relevant C2C project hypotheses as follows:

1. The C2C method will release significant capacity to customers from existing infrastructure.

   C2C operation, through the use of DSR and interconnected network operation, has the potential to accommodate a significant increase in demand and DG connections on HV circuits.

2. The C2C method will enable improved utilisation of network assets through greater diversity of customers on the network ring.

   This hypothesis can be validated in two parts. First, the increase in demand and DG capacity due to C2C operation, specifically due to DSR, leads to improved utilisation of existing assets, without requiring reinforcement. Second, there is a greater opportunity for improved demand diversity through interconnected (closed-ring) operation because when more customers are connected to a ring there is more diversity; this has been demonstrated using historical demand data.

3. The C2C method will reduce like-for-like power losses initially but this benefit will gradually erode as newly released capacity is utilised.

   This hypothesis can be validated in two parts. First, there is an initial reduction in losses that can be gained through closing the NOP which, at the maximum level of demand without C2C deployment or reinforcement, results in an average decrease in peak instantaneous losses of 8% for the studied circuits. Second, as demand increases beyond the capacity of conventional network, facilitated by C2C operation and the consequent avoidance of reinforcement, there is an increase in losses relative to radial reinforced networks.

4. The C2C method will improve power quality resulting from stronger electrical networks.

   Theoretical studies and detailed system monitoring have determined that C2C operation is likely to have only a marginal impact on power quality. The future growth in demand and generation may affect power quality, but this depends on the type of the connection.
8.3 Additional learning outcomes

8.3.1 Interconnected C₂C operation generally releases more demand capacity than Radial C₂C operation

Interconnected C₂C operation typically facilitates HV network configurations where one feeder is relatively more heavily loaded than the other feeder comprising the ring circuit; the lower-loaded feeder can supply load current to the other feeder, via the NOP, thereby “balancing” the power flows across both feeders. Such configurations improve the utilisation of existing assets but are not possible with the defined Radial C₂C methodology. In some cases, Radial C₂C operation can release more demand capacity than Interconnected C₂C, and this generally occurs when one feeder comprising the ring circuit has a higher impedance than the other feeder.

Similarly, Interconnected C₂C operation generally releases more DG capacity than Radial C₂C operation.

8.3.2 Interconnected C₂C operation generally results in slightly lower losses than Radial C₂C operation

On average, at maximum C₂C demand, there is a marginal reduction in losses of approximately 0.09% (as a percentage of demand) for Interconnected C₂C operation as opposed to Radial C₂C operation.

8.3.3 Results cannot be generalised by circuit type

The results for demand capacity, DG capacity, and losses depend significantly on individual circuit topologies, the ratings of circuit sections, and load or DG locations. There is substantial variation in these characteristics throughout the circuits considered in this report. It is therefore difficult to generalise the results for a specific circuit type, e.g., by urban vs. rural feeders, or by load type. Bespoke system modelling, as performed for the studies in this report, is required to quantify the impact of C₂C operation for each application to HV circuits.

8.3.4 The demand growth methodology affects Radial C₂C asset utilisation

The methodology for assessing the demand released by C₂C operation assumes uniform growth in demand that is proportional to existing load capacities. In some cases, for Radial C₂C operation, this approach may appear to lead to under-utilisation of one of the HV feeders comprising the ring circuit. This is because the adopted methodology considers that each individual feeder cannot be loaded up to its limit independently of the other feeder; both feeders are limited by a constraint on either feeder. If the NOP location was re-selected to “balance” the two feeders prior to interconnection, if possible, then these scenarios (where load is concentrated on one feeder) would generally be avoided – meaning that Radial C₂C operation would always be preferable (or equal to Interconnected C₂C) in order to maximise released demand capacity.
Appendix A: Electrical System Modelling

A.1 Overview

Figure 70 illustrates the overall process for creating the system model for each ring circuit and for undertaking load flow studies. The process is generic – it is applicable to all modelled C2C trial ring circuits – and is fully automated (following some initial configuration). The following subsections describe the process steps in detail.

A.2 Assumptions

The following assumptions have been used in this methodology:

1. Nominal line voltage, either 6.6 kV or 11 kV, is assumed at the primary busbar.
2. No distributed generation (DG) is included (unless required for specific scenarios).
3. To determine capacity limits, load ratings for each feeder are scaled linearly from the base rating. This is achieved by multiplying the load real and reactive power ratings by a scaling factor. For simplicity and to cater for the worst case peak demand, no load profiling has been performed.

A.3 Data sources

Appendix E provides a detailed description and comparison of the applicable data sources available from ENWL. The following data sources have been used to establish the radial capacity limits:

- DINIS network data for each ring circuit.
- ENWL Codes of Practice plus supplementary overhead line and cable data sheets, for mapping DINIS line types to impedance and thermal ratings. Due to limitations within the available data, the “cyclic” thermal rating value for each line and cable type has been used for all system intact studies, regardless of the time of year or ambient temperature.
- Operational diagrams for all ring circuits involved in the C2C trial.

Figure 70: Circuit process steps
Further to Appendix E, Table 17 outlines the conventions that have been used for impedance, line thermal rating, and length units. These conventions were closely adhered to during the course of the analysis work.

<table>
<thead>
<tr>
<th></th>
<th>DINIS</th>
<th>Line mapping spreadsheet</th>
<th>DINIS to IPSA import script</th>
<th>Code of Practice documents</th>
<th>IPSA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Line Impedances</strong></td>
<td>% on a 100 MVA base (not used)</td>
<td>Ω/km</td>
<td>pu/km</td>
<td>Ω/km and % on a 100 MVA base (at 11 kV)</td>
<td>pu (pu/km for database items)</td>
</tr>
<tr>
<td><strong>Line Thermal Ratings</strong></td>
<td>A (not used)</td>
<td>MVA</td>
<td>A</td>
<td>A</td>
<td>MVA (Send and receive in kA)</td>
</tr>
<tr>
<td><strong>Line Lengths</strong></td>
<td>mm</td>
<td>n/a</td>
<td>m</td>
<td>n/a</td>
<td>n/a (km for database items)</td>
</tr>
</tbody>
</table>

Table 17: Conventions for units

**A.4 Automatic circuit conversion from DINIS to IPSA**

IPSA has been used for modelling system power flows to establish circuit capacities for the following reasons:

- It can be readily scripted using the Python programming language, which is particularly important for incorporating data from various sources such as spreadsheets, and for defining and simulating arbitrary scenarios.
- It is familiar to personnel at ENWL and the University of Strathclyde.
- It is possible to automatically convert DINIS models to IPSA files.

IPSA version 2 includes a template script, in Python, for importing DINIS data files. This script has been significantly extended and modified by the University of Strathclyde to cater for the analyses required within the C2C project. The script performs the functions described in the following subsections. For each imported circuit, the generated IPSA model has been manually verified by comparison with ENWL Operational Diagrams (CAD drawings of each circuit).

**A.4.1 Basic DINIS file import**

1. All DINIS data are converted to Python objects. The electrical connectivity is gleaned by “snapping” together x- and y-coordinates. A full IPSA representation of the DINIS data, using geographical coordinates, is created.
   a. All loads are modelled as constant power type.
b. Line and cable data are obtained from a lookup table within a separate file. The conductor thermal ratings used are either cyclic or distribution ratings (see [5], page A2), rather than continuous ratings.

c. Multi-segment lines are supported.

d. Duplicate node names are not permitted by the import script, and must be manually renamed within the DINIS source file, if needed.

2. The entire process is scripted to iterate through all 36 ring circuits automatically.

3. All the “linecodes” used to identify each branch type used throughout all 36 ring circuits are automatically recorded. This facilitates maintaining accurate and consistent records of the branch impedance and thermal rating values.

A.4.2 Ring circuit isolation

4. The connectivity between all busbars and branches\textsuperscript{12} is explicitly added to the Python objects to assist with later stages of the conversion process.

5. A graph of the network is created, as illustrated in Figure 71, where busbars are vertices and branches are edges. This allows established graph theory methods (and available Python libraries) to be used to assist with the conversion process.

   a. The edges can be weighted by the total branch length or by impedance (resistive, reactive, or impedance magnitude).

6. Information about the ring circuit – including the secondary substation(s) at the start of each feeder and the NOP location – is imported from an external file.

   b. This information has been manually compiled by consulting the Operational Diagrams and the DINIS files.

7. Branches which are connected to busbars which are not rated at the primary busbar nominal voltage, or which represent transformers, are excluded from the graph. All superfluous branches which are specified as NOPs are also excluded. The ring circuit of interest is thereby isolated from the rest of the model.

   a. In some cases, NOPs are missing in the DINIS data, but are present in the Operational Diagrams. Special cases have been created to ensure that these NOPs are preserved correctly.

   b. In some cases, the NOP for the ring circuit occurs at or close to the primary busbar. The import process caters for this scenario.

8. The primary busbar is located using Dijkstra’s algorithm [21] to find the shortest path between the two (or more) secondary substation busbars at the start of each feeder. This is necessary because each primary busbar consists of a complicated arrangement of many interconnected nodes within the DINIS data.

   a. Extraneous, “dangling” nodes are trimmed from the primary busbar.

\textsuperscript{12} The terms “busbars” and “branch” are used within IPSA. A branch refers to any line or cable which interconnects two busbars. A branch may have multiple circuit sections. Within DINIS data, the term “node” is used, but “node” is generally interchangeable with “busbar”.
b. The node at the mid-point of the primary busbar nodes is estimated, and a grid infeed (an IPSA component) is connected to it. This node is set as the slack bus for IPSA load flows.

9. Starting from one of the substations at the start of a feeder, a tree is built from the remaining nodes, using a depth-first search algorithm [22]. This is illustrated in Figure 72. This ensures that all extremities of the radial circuits which make up the ring circuit are found. All other branches, nodes, loads, and generators (if applicable) are removed from the IPSA model.

10. The NOP for the ring circuit is restored to the network graph. The NOP is initially opened by switching-out the branch in IPSA, and by setting the edge weight within the graph to a large number. The large edge weight ensures that a shortest path algorithm will always favour a route via the primary busbar, rather than via the NOP.

Figure 71: Ring circuit graph representation
A.4.3 Load scaling

11. The loads are allocated into two groups: connected to feeder A, or connected to feeder B. The loads for each group can be scaled independently, if required.

12. Initially, the load ratings are specified based on the apparent power rating given in the DINIS data, which is based on the HV/LV transformer ratings or maximum demand indicators. A power factor of 0.95 lagging is assumed when specifying the real and reactive power ratings of loads in IPSA, which are modelled as constant power loads.

13. Depending on the scenario of interest, all load ratings are linearly scaled by a global scaling factor in IPSA to emulate uniform growth in demand. Typically, the scaling factor is increased in increments of 0.01 and a load flow is performed until a thermal constraint (by comparing simulated power flows to conductor ratings) or a voltage constraint (by comparing busbar voltages to regulatory limits) is experienced in the circuit. A linear increase in the scaling factor is used to find the capacity limits, rather than an alternative search method, to fully characterise the behaviour of circuit losses as demand increases.

A.4.4 Generating results
For each scenario, as described throughout this report, a number of IPSA load flow and fault level simulations are performed. The results are recorded in a Python data structure which can be analysed directly or can be automatically exported as other formats, such CSV files.

A.5 Implementation details

The process described in this appendix uses the “native” Python IPSA interface, rather than being invoked from the IPSA graphical user interface. This allows the IPSA import process and all simulations to be fully automated.

A multi-process, parallel code execution system and an efficient CPU core “pooling” technique have been developed to significantly reduce execution times. This ensures that the automated processing of all 36 modelled circuits is efficiently spread across all CPU cores within a multi-core CPU. For example, using a quad-core CPU, execution times are reduced by approximately a factor of four. This method could also be applied to any IPSA modelling task which involves more than one IPSA model, or which involves multiple distinct experiments using a single IPSA model.

As described in Section A.4.4, a data structure for storing the results of all IPSA simulations and other circuit “meta-data” has been established. This has the following advantages:

- It provides a consistent interface for dynamically performing data analysis and generating expressive visualisations of the data.
- Using facilities in Python, the results are automatically cached in a database local file, and later reloaded without the need to execute the entire simulation process. If the circuit analysis process is updated (i.e., the code is edited), the database cache file is automatically refreshed.

A.6 Typical circuit data

This section illustrates the model development process in detail for a single ring circuit connected to the 6.6 kV Denton East primary substation (located east of Manchester city centre). The process is identical for all other circuits analysed. This ring circuit involves only cables (rather than overhead lines), and the loads are predominantly domestic in nature. The Operational Diagram for this circuit is presented in Figure 73, with the particular ring circuit of interest highlighted within the perimeter of the dashed line on the figure.
Figure 73: Operational Diagram of Denton East primary, highlighting the ring circuit of interest

The entire Denton East primary and associated circuits can be imported into IPSA and displayed geographically as shown in Figure 74.
Figure 74: Full extent of the circuits connected to Denton East primary presented in IPSA
(6.6 kV in blue, 33 kV in green)

Figure 75 illustrates the final, simplified IPSA model containing only the ring circuit of interest. This model is generated automatically by the import script developed at the University of Strathclyde as described in this appendix. The primary busbar and NOP are highlighted in Figure 75. Although not shown (due to the nature of IPSA’s Python interface), a grid infeed is connected at the primary busbar, and a constant power load has been simulated at each of the eleven named substations on this circuit. The nodes labelled “EDMC000RNY” and “EDMC000RKK” are used for connectivity and do not represent actual substations or loads. Due to the detailed connectivity used within the DINIS model, the primary busbar consists of a cluster of several nodes, which are interconnected by zero-impedance connections.
Figure 75: 6.6 kV ring circuit of interest at Denton East primary, modelled in IPSA
Appendix B: Effects of Modelled DG Power Factor

B.1 DG capacity released

The selection of DG power factor slightly affects the results for released DG capacity. This is illustrated in Figure 76 for a power factor of 0.95 lagging, which results in a slight decrease in the average released DG capacity, compared to unity power factor as assumed in Chapter 4.

Similarly, a 0.95 leading power factor results in an increase in the average released DG capacity, compared to unity power factor, as shown in Figure 77. This is due to the fact that the increase in the reactive power flowing out of the primary causes an increased voltage drop which partly mitigates the voltage rise at the DG terminals, which in turn allows more DG capacity to be accommodated in some cases.
B.2 Constraint types for unity DG power factor

The types of constraints – voltage or thermal – experienced for maximum connected DG, assuming uniform DG growth, are summarised in Table 18. For the DG base case, all constraints are due to voltage constraints (where the HV voltage is greater than 1.012 pu), and are typically experienced at DG locations relatively far from the primary. This can be attributed to the relatively large electrical distance between remote DG connections and the primary substation during the worst case N-1 conditions. The flow of the power exported from the DG through the associated impedance causes the voltage to rise above the nominal voltage at the primary.

At unity power factor, there is almost no difference in the types of constraints experienced between Radial C2C and Interconnected C2C. For the “Dickinson Street” circuit, Interconnected C2C operation results in a thermal constraint rather than the voltage constraint experienced for Radial C2C operation (resulting in an overall increased proportion of thermal constraints from 11% to 14%). This is due to the change in power flows resulting from closing the NOP, which leads to a thermal constraint at a higher level of released DG capacity, because the voltage constraint is mitigated.
B.3 Constraint types for lagging and leading DG power factors

As can be observed in Table 19, a leading DG power factor results in a greater proportion of thermal constraints than voltage constraints, compared to unity or lagging power factor. As noted in Appendix B, this allows more DG capacity to be released, i.e., it leads to better utilisation of the HV circuits. Conversely, a lagging power increases the proportion of voltage constraints and generally reduces the released DG capacity.

<table>
<thead>
<tr>
<th>Power factor</th>
<th>Voltage</th>
<th>Thermal</th>
<th>Voltage</th>
<th>Thermal</th>
<th>Voltage</th>
<th>Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unity</td>
<td>100%</td>
<td>0%</td>
<td>89%</td>
<td>11%</td>
<td>86%</td>
<td>14%</td>
</tr>
<tr>
<td>0.95 lagging</td>
<td>100%</td>
<td>0%</td>
<td>94%</td>
<td>6%</td>
<td>92%</td>
<td>8%</td>
</tr>
<tr>
<td>0.95 leading</td>
<td>100%</td>
<td>0%</td>
<td>89%</td>
<td>11%</td>
<td>81%</td>
<td>19%</td>
</tr>
</tbody>
</table>

Table 19: Summary of constraint types for uniform growth in DG, at different power factors
Appendix C: Processing Raw Demand Data

The raw half-hourly primary feeder demand data for 366 days for all 72 radial circuits has been provided in a text-based format, and a MATLAB script has been used to process the data and convert it into a form which is suitable for subsequent stages of the analysis work. In particular, the MATLAB script caters for the following issues with the circuit demand data:

- In total, 5612 half-hourly current measurement values are missing. This equates to 0.44% of the total number of values, or 1.62 days cumulatively across all 72 modelled feeders. The reason for the missing data is unknown, but it is likely to be due to failure of a remote terminal unit (RTU) or an element within the communications system.

- There are 140 entries where a single measurement value is missing. These missing values have been estimated by linear interpolation of the two adjacent half-hourly values. It is also possible to interpolate from the previous and following days, but the differences between weekdays and the weekend could be significant, so this approach has not been used. It is also possible to interpolate data from the previous and following weeks, but for simplicity this approach has not been chosen.

- In 114 cases, all measurement values for a feeder are missing for an entire day, i.e., in total 5472 such values are missing. This represents 0.43% of the total data. In some cases, this occurs for several consecutive days. In the worst case, data are missing for 14 consecutive days for four different measurement locations. For simplicity, a measurement value of 0 A will be assumed. This assumption will not affect the peak demand value, and should have minimal impact on the mean demand value.\(^\text{13}\)

- 15 measurement values are greater than 700 A, and some values are as high as 6-7 kA. In some cases, several measurement values are continuously or periodically “frozen” at a particular value, which suggests a spurious measurement. These are assumed to be erroneous, and any value greater than 700 A has been removed and interpolated from adjacent values.

- If any measurement value is greater than 4 standard deviations from the year mean, or is greater than 3 standard deviations from the day mean, it is deemed spurious. The spurious data points are interpolated from the adjacent weeks (where possible) due to the presence of consecutive sequences of spurious data. These thresholds have been chosen because they remove spurious data, without affecting normal trends (from a visual comparison of the data). This method of spurious data detection is known as Chebyshev’s inequality and its use for filtering demand data is described in [23].

Figure 78 illustrates the raw and processed demand data for one of the feeders connected at the “Ashton on Mersey” primary substation. In the raw data, a

\(^{13}\) The assumption of using 0 A values for 14 days of data for one feeder will result in approximately a 4% reduction in the calculated mean feeder demand value.
sequence of relatively large spurious measurements of approximately 350 A can be seen; these data are correctly removed, as seen in the processed data. There is no visible distortion to the other data. Similarly, visual checks have been used to validate the all the results from this process.

**Figure 78: Comparison of raw and processed feeder demand data**
Appendix D: Sensitivity of Losses to Load Type

The simulation studies presented in Chapter 5 assume constant power loads. This may tend to represent the worst case for losses because any voltage drop in a circuit will result in higher current being drawn by a constant power load connected at this location. Losses are proportional to the square of current, and therefore losses grow quadratically as current increases. In contrast, a constant impedance load would counter the effects of lower voltage by drawing a lower current, with losses reducing quadratically. In reality, the loads connected to a distribution system are a mix of constant power and constant impedance loads. Constant impedance loads are considered to be more representative of domestic loads; however because the actual mixture of loads was not known, both approaches should be regarded as approximations.

Although IPSA can simulate ZIP loads (a combination of constant impedance, constant current, and constant power loads) these models cannot be controlled from the Python scripting interface – which is necessary for automatically assessing the impact of C2C operation across multiple circuits. Constant impedance shunts could instead be used to model constant impedance loads. However, for flexibility, a script has been created which dynamically alters the rating of all constant power loads to mimic the behaviour of constant impedance loads, depending on the load voltage. This process requires several iterations to converge, where each iteration involves executing a load flow followed by adjustment of the load rating. Therefore, the two extreme cases to be compared: all loads constant power vs. all loads constant impedance.

Figure 79 compares the impact of load type on losses for all 36 modelled circuits using box plots. The same level of demand – the maximum capacity which can be released by each circuit for both load types, assuming Interconnected C2C operation – is used for comparison between load types. The two distributions are very similar, but with fractionally higher losses for constant power loads.

Figure 79: Box plots comparing impact of load type on losses
Figure 80 compares the trends of losses for each circuit. By modelling loads as constant impedances, the capacity released by $C_2C$ is slightly higher in most cases. The maximum reduction in losses for constant impedance load models, as a percentage relative to constant power load models (at the same level of demand), is indicated for each ring circuit. At most, modelling loads at constant impedance reduces losses by 4.7%, for a given demand. For context, Figure 81 illustrates the losses assuming rated loading, i.e., the losses are plotted against the load scaling factor multiplied by the equivalent load rating at nominal voltage.

At most there is only a relatively small variation in voltage permitted within the simulated circuits; i.e., between 1.0 pu (at the primary) and the lower regulatory limit of 0.94 pu (assuming no generation is connected). Such extreme voltage drops are typically only experienced on rural circuits which also typically have relatively low loading at the circuit extremities. Therefore, results for the two load types are very similar, with the exception of a few circuits.

In conclusion, the losses results in Chapter 5 are not expected to be affected significantly by the load model. Constant power loads offer simplicity in their modelling and a more conservative approach in terms of evaluating losses (i.e., will tend to slightly overestimate losses), and therefore they were considered to be the most suitable approach.
Figure 80: Impact of load type on losses, for actual demand
Figure 81: Impact of load type on losses, assuming demand at nominal voltage
Appendix E: Assessment of ENWL Network Data Sources

Table 20 summarises various data inputs which were required for undertaking the simulation studies, and potential sources of the data. Positive information – i.e., where the data source meets the requirements for modelling – is shown in green text and negative information is shown in red text. Neutral information (neither overly positive nor negative) is given in black text. The following can be noted:

1. For each row, at least one data source satisfies the requirements. However, this necessitates integration of the various data sources.
2. The Common Information Model (CIM) model does not have any containment, i.e., it is missing Substation, VoltageLevel, and Line instances. The model would fail validation against a CIM Profile.
3. The CIM model does not conform to the standard for storing impedance data. Impedance values should be stored in ohm, but the ENW CIM model uses ohm/km.
<table>
<thead>
<tr>
<th>Data format</th>
<th>CIM model</th>
<th>DINIS files</th>
<th>Code of Practice documents</th>
<th>Line type half-hourly feeder current measurements</th>
<th>Operational Diagrams (CAD drawings)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standardised data format, based on XML and RDF. Strathclyde has extensive experience with CIM, and has access to software for managing CIM models.</td>
<td>Structured data format, but very complex and polymorphic. The files are text-based, but are not easily human-readable. However, IPSA can import DINIS files and this process is partially automated.</td>
<td>PDF of tabular data</td>
<td>Spreadsheet</td>
<td>Spreadsheet</td>
<td>AutoCAD files – requires software to view</td>
</tr>
<tr>
<td>Electrical connectivity (including all secondary substations)</td>
<td>Yes</td>
<td>Yes, but must be gleaned by “snapping” coordinates together</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Source impedance and X/R ratios at HV primary substations</td>
<td>No, but could be based on primary transformer ratings</td>
<td>No, but could be based on primary transformer ratings</td>
<td>Yes, assumed fault level at 6.6/11 kV specified</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Line types (OHL or cable)</td>
<td>Yes</td>
<td>Yes, but supporting document (spreadsheet) must be consulted</td>
<td>No, only some included; does not match CIM model</td>
<td>Yes</td>
<td>n/a</td>
</tr>
<tr>
<td>Line impedances (or per-length impedances and lengths)</td>
<td>Yes: R, X, R₀, X₀ (all per-length) and line lengths</td>
<td>Yes, lengths are given but supporting document</td>
<td>No, only some included; does not</td>
<td>Yes</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Source impedance and X/R ratios at HV primary substations:
- No, but could be based on primary transformer ratings
- No, but could be based on primary transformer ratings
- Yes, assumed fault level at 6.6/11 kV specified

Line types (OHL or cable):
- Yes
- Yes, but supporting document (spreadsheet) must be consulted
- No, only some included; does not match CIM model

Line impedances (or per-length impedances and lengths):
- Yes: R, X, R₀, X₀ (all per-length) and line lengths
- Yes, lengths are given but supporting document
- No, only some included; does not
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Details</th>
<th>Match CIM Model</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Line thermal/current ratings</strong></td>
<td>No, must be mapped to definitions in the supporting document (spreadsheet). (Circuit breaker rated current values are available.)</td>
<td>No, line ratings (in Amps or MVA) are missing, but are defined in the supporting document (spreadsheet)</td>
<td>Yes</td>
<td>n/a</td>
</tr>
<tr>
<td><strong>Transformer ratings, impedances, and losses</strong></td>
<td>Rated apparent power, rated voltage, R, X, R₀, and X₀ are provided</td>
<td>No, only some included; does not match CIM model</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td><strong>Estimation of peak and mean load power ratings for all loads</strong></td>
<td>No, all AnalogValue instances (some of which represent power or current measurements) have a value of 0.0</td>
<td>Load ratings are provided (actual load in kVA and power factor), but it is not clear where these loads are located – a full topological analysis would need to be carried out</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
2. Current data is single-phase, so balanced conditions must be assumed.
3. Some data values are missing, but interpolation is possible.

<table>
<thead>
<tr>
<th>Distributed Generation data</th>
<th>76 EnergySource instances are defined, along with the “active power” rating</th>
<th>Data for synchronous machines available, including inertia and d-q reactance/time values</th>
<th>No</th>
<th>n/a</th>
<th>n/a</th>
<th>No (apart from location)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOP location</td>
<td>No, all normalOpen values are false</td>
<td>No: for some circuits the NOP is explicitly specified, but this is not the case for most circuits.</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>Yes</td>
</tr>
<tr>
<td>Locations/geographical data (optional)</td>
<td>No</td>
<td>Yes</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 20: Summary of ENWL network data sources
Appendix F: Voltage Harmonic Distortion Simulation Parameters

F.1 Parameters for simplified examples

Table 21 summarises the parameters used for the simplified voltage harmonic distortion examples in Section 6.2.3.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_s$</td>
<td>11 kV</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.095 Ω</td>
</tr>
<tr>
<td>$X_s$</td>
<td>0.475 Ω</td>
</tr>
<tr>
<td>$R_N$</td>
<td>6.0 Ω (typical value from [24])</td>
</tr>
<tr>
<td>$R_A, R_B, R_{NOP}$</td>
<td>0.1 Ω/km (typical value from [8])</td>
</tr>
<tr>
<td>$X_A, X_B, X_{NOP}$</td>
<td>0.1 Ω/km (typical value from [8])</td>
</tr>
<tr>
<td>Feeder A length</td>
<td>2 km</td>
</tr>
<tr>
<td>Feeder B length</td>
<td>2 km</td>
</tr>
<tr>
<td>NOP branch length</td>
<td>0 km</td>
</tr>
<tr>
<td>Load A</td>
<td>Constant impedance, 2 MVA at unity power factor</td>
</tr>
<tr>
<td>Load B</td>
<td>Constant impedance, 2 MVA at unity power factor</td>
</tr>
</tbody>
</table>

Table 21: Simulation parameter values for simplified examples

F.2 Simplified examples with background harmonics

Table 22 summarises further examples, similar to the examples from Table 6 in Section 6.2.3.2, but with background harmonic injection at the primary substation. The following differences between Table 6 and Table 22, due to the presence of background harmonics, can be observed:

1. The THD values at each location are generally higher due to the additional harmonic injection.
2. Example 5 illustrates that background harmonics can have an effect, albeit practically negligible, on the change in THD at secondary substations due to interconnected operation, if the feeder impedances are asymmetrical.
3. The results for Example 7 are similar to Example 1 in Section 6.2.3.2. Therefore harmonic injection at the primary does not have a significant impact on the change in THD when the secondary harmonic injection is asymmetrical.
4. Example 8, with feeder length asymmetry compared to Example 6, results in a very slight increase in THD at the primary for interconnected operation, compared with radial operation. This is due to the change in the phase of the voltage distortion from $HI_A$ and $HI_B$ due to the change in feeder impedance resulting from interconnected operation; the vector sum of the voltage distortion from $HI_A$ and $HI_B$ “constructively interferes” to a greater extent with
the voltage distortion from $H_{1p}$. However, this effect is negligible for realistic feeder lengths and will only occur for harmonics at the same frequencies.

5. In Example 9, for interconnected operation a proportion of the harmonic injection from Feeder B flows to the primary substation via Feeder A. Therefore the THD at Feeder A increases when the circuit operates interconnected. In this case, the vector sum of the voltage harmonic distortion at the primary is unchanged for both radial and interconnected configurations, and is the same as for Example 4; i.e., the voltage distortion from the secondary substations is cancelled-out at the primary. The relative phases of the background harmonic injection and the secondary harmonic injection (at each harmonic frequency) will dictate the aggregate THD at the primary.

<table>
<thead>
<tr>
<th>Description</th>
<th>Example 4</th>
<th>Example 5</th>
<th>Example 6</th>
<th>Example 7</th>
<th>Example 8</th>
<th>Example 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeder A length</td>
<td>2 km</td>
<td>4 km</td>
<td>2 km</td>
<td>2 km</td>
<td>4 km</td>
<td>2 km</td>
</tr>
<tr>
<td>Feeder B length</td>
<td>2 km</td>
<td>2 km</td>
<td>2 km</td>
<td>2 km</td>
<td>2 km</td>
<td>2 km</td>
</tr>
<tr>
<td>NOP branch length</td>
<td>0 km</td>
<td>0 km</td>
<td>0 km</td>
<td>0 km</td>
<td>0 km</td>
<td>0 km</td>
</tr>
<tr>
<td>“Background” primary harmonic injection ($H_{1p}$)</td>
<td>5th, 23rd (both 5 A, 0°)</td>
<td>5th, 23rd (both 5 A, 0°)</td>
<td>5th, 23rd (both 5 A, 0°)</td>
<td>5th, 23rd (both 5 A, 0°)</td>
<td>5th, 23rd (both 5 A, 0°)</td>
<td>5th, 23rd (both 5 A, 0°)</td>
</tr>
<tr>
<td>Load A</td>
<td>2 MVA</td>
<td>2 MVA</td>
<td>2 MVA</td>
<td>2 MVA</td>
<td>2 MVA</td>
<td>2 MVA</td>
</tr>
<tr>
<td>$H_{1A}$ harmonic numbers</td>
<td>None</td>
<td>None</td>
<td>5th, 23rd</td>
<td>5th, 23rd</td>
<td>5th, 23rd</td>
<td>5th, 23rd</td>
</tr>
<tr>
<td>$H_{1A}$ harmonic magnitudes</td>
<td>0 A, 0 A</td>
<td>0 A, 0 A</td>
<td>5 A, 5 A</td>
<td>10 A, 10 A</td>
<td>5 A, 5 A</td>
<td>5 A, 5 A</td>
</tr>
<tr>
<td>$H_{1A}$ harmonic phases</td>
<td>0°, 0°</td>
<td>0°, 0°</td>
<td>0°, 0°</td>
<td>0°, 0°</td>
<td>0°, 0°</td>
<td>180°, 180°</td>
</tr>
<tr>
<td>Load B</td>
<td>2 MVA</td>
<td>2 MVA</td>
<td>2 MVA</td>
<td>2 MVA</td>
<td>2 MVA</td>
<td>2 MVA</td>
</tr>
<tr>
<td>$H_{1B}$ harmonic numbers</td>
<td>None</td>
<td>None</td>
<td>5th, 23rd</td>
<td>5th, 23rd</td>
<td>5th, 23rd</td>
<td>5th, 23rd</td>
</tr>
<tr>
<td>$H_{1B}$ harmonic magnitudes</td>
<td>0 A, 0 A</td>
<td>0 A, 0 A</td>
<td>5 A, 5 A</td>
<td>5 A, 5 A</td>
<td>5 A, 5 A</td>
<td>5 A, 5 A</td>
</tr>
<tr>
<td>$H_{1B}$ harmonic phases</td>
<td>0°, 0°</td>
<td>0°, 0°</td>
<td>0°, 0°</td>
<td>0°, 0°</td>
<td>0°, 0°</td>
<td>0°, 0°</td>
</tr>
</tbody>
</table>

| $\delta THD$ at primary substation | No change (0.55%) | No change (0.55%) | No change (1.63%) | No change (2.18%) | Increase (1.61% to 1.62%) | No change (0.55%) |
| $\delta THD$ at secondary substation A | No change (0.54%) | Increase (0.531% to 0.538%) | No change (1.86%) | Decrease (2.52%) | Decrease (2.05% to 1.92%) | Increase (0.30% to 0.54%) |
| $\delta THD$ at secondary substation B | No change (0.54%) | Decrease (0.540% to 0.538%) | No change (1.86%) | Increase (2.40% to 2.52%) | Increase (1.84% to 1.92%) | Decrease (0.80% to 0.54%) |

Table 22: Effects of harmonic magnitude, feeder length, and harmonic phase on THD (with background harmonics)

F.3 Parameters for Monte Carlo simulations

Table 23 summarises the ranges of parameters from which random values are selected for each Monte Carlo iteration (expect where fixed for Scenarios 2 and 3)
from Section 6.2.4. A uniform distribution is used for all random variables, except for load power factor which uses a normal distribution (so that unity power factor is generally more likely than a purely reactive load). The Load A and Load B apparent power is fixed at 2 MVA but the magnitudes of the harmonic injection associated at each secondary substation is varied independently. The number of iterations for each scenario is 20000.

As for the examples given in Section 6.2.3.2, two harmonic frequencies are selected for each harmonic injection location, although the harmonic frequencies are chosen randomly for each Monte Carlo iteration.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum value</th>
<th>Maximum value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{I_p}$ harmonic numbers</td>
<td>2nd</td>
<td>23rd</td>
<td>Two random harmonics are selected</td>
</tr>
<tr>
<td>$H_{I_p}$ harmonic magnitudes</td>
<td>0 A</td>
<td>2 A</td>
<td></td>
</tr>
<tr>
<td>$H_{I_p}$ harmonic phases</td>
<td>-180°</td>
<td>180°</td>
<td></td>
</tr>
<tr>
<td>Load A</td>
<td>2 MVA, leading power factor</td>
<td>2 MVA, lagging power factor</td>
<td>Load rating is fixed, only power factor varies</td>
</tr>
<tr>
<td>$H_{I_A}$ harmonic numbers</td>
<td>2nd</td>
<td>23rd</td>
<td>Two random harmonics are selected</td>
</tr>
<tr>
<td>$H_{I_A}$ harmonic magnitudes</td>
<td>0 A</td>
<td>2 A</td>
<td></td>
</tr>
<tr>
<td>$H_{I_A}$ harmonic phases</td>
<td>-180°</td>
<td>180°</td>
<td></td>
</tr>
<tr>
<td>Load B</td>
<td>2 MVA, leading power factor</td>
<td>2 MVA, lagging power factor</td>
<td>Load rating is fixed, only power factor varies</td>
</tr>
<tr>
<td>$H_{I_B}$ harmonic numbers</td>
<td>2nd</td>
<td>23rd</td>
<td>Same values as used for $H_{I_A}$ (except for Scenario 2)</td>
</tr>
<tr>
<td>$H_{I_B}$ harmonic magnitudes</td>
<td>0 A</td>
<td>2 A</td>
<td>Same values as used for $H_{I_A}$</td>
</tr>
<tr>
<td>$H_{I_B}$ harmonic phases</td>
<td>-180°</td>
<td>180°</td>
<td></td>
</tr>
<tr>
<td>Feeder lengths</td>
<td>0.5 km</td>
<td>4.0 km</td>
<td>$R = 0.1 , \Omega/km, X = 0.1 , \Omega/km$</td>
</tr>
<tr>
<td>NOP branch length</td>
<td>0.2 km</td>
<td>1.5 km</td>
<td>$R = 0.1 , \Omega/km, X = 0.1 , \Omega/km$</td>
</tr>
</tbody>
</table>

Table 23: Summary of parameters used for Monte Carlo simulations

F.4 Effects of other factors

F.4.1 Harmonic frequency
Repeating the Monte Carlo simulations with higher harmonics (24th to 50th), but with similar magnitudes, results in a similar distribution to Figure 53, but over a slightly wider range or values. This is due to the higher impedance experienced by higher harmonics, resulting in higher voltage THD values.

**F.4.2 Other modelling details**

The choice of $Z_s = 0.484$ Ω, which equates to an upstream fault level contribution of 250 MVA, is the worst case for fault levels at HV, and is therefore the best case for minimising THD in the HV system. The choice of source impedance affects numerical results, but does not affect the overall impact of C2C operation on THD.

Star-connected harmonic injection is assumed with no earth connection at the neutral point.

The potential impact of harmonic resonances is ignored in these studies.
Appendix G: Power Quality Monitoring Data Import and Validation Process

G.1 Introduction

This appendix summarises the status of the data extracted from the PQube power quality monitoring devices used for the C2C project. Monitoring data are stored on memory cards which must be manually collected from each monitoring location and then physically delivered to the University of Strathclyde. This report provides an appraisal of the three “batches” of monitoring data which have been captured during approximately February 2013 to June 2014.

This appendix assesses the validity of all captured monitoring data, including: data corruption, configuration issues, and time synchronisation. The suitability for the monitoring data to support the C2C project power quality analysis work is thereby quantified.
G.2 Overview of data

G.2.1 SD card “batches"

The PQube power quality monitoring devices are installed at 77 secondary substations throughout the 36 C2C trial ring circuits, with at least two PQube devices located per circuit. A PQube device is shown in Figure 57.

![Figure 82: PQube device (sensors and enclosure not shown)](image)

Monitoring data are stored on Secure Digital (SD) flash memory cards which must be manually collected from each monitoring location, rather than the use of data communications and a centralised data storage service. Three “batches” of SD card data have been collected and copied by ENWL and delivered to the University of Strathclyde.

Within an SD card collected from a PQube device, the monitoring data are stored in comma-separated values (CSV) files, with separate files for:

- Monthly trends (5-minute sampling),
- Weekly trends (5-minute sampling), and
- Daily trends (1-minute sampling).

Note that this arrangement results in some redundancy because the monthly and weekly trends CSV files ultimately contain the same data, and the daily trend CSV files contain the superset of all sampled data. The detailed harmonics data – up to the 63rd harmonic with inter-harmonics, per-phase for voltage and current – are stored in separate CSV files which are captured using a 15-minute sampling period.

G.2.2 Raw SD card data

Table 24 summarises each batch of data.
Table 24: Summary of batch data size

<table>
<thead>
<tr>
<th>Approximate date range</th>
<th>Batch 1</th>
<th>Batch 2</th>
<th>Batch 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 2013 – Jun 2013</td>
<td>158 GB</td>
<td>277 GB</td>
<td>149 GB</td>
</tr>
<tr>
<td>Jun 2013 – Feb 2014</td>
<td>2.18 million</td>
<td>3.54 million</td>
<td>1.92 million</td>
</tr>
<tr>
<td>Feb 2014 – Jun 2014</td>
<td>0.96 million</td>
<td>1.60 million</td>
<td>0.94 million</td>
</tr>
</tbody>
</table>

| Number of Files       | 2.18 million | 3.54 million | 1.92 million |
| Number of directories | 0.96 million | 1.60 million | 0.94 million |
| Locations with monitoring data | 71 | 64 | 60 |
| Date received at the University of Strathclyde | 26th Jan 2014 | Approx. 11th Jun 2014 | 2nd Jul 2014 |

Table 25, Table 26, and Table 27 summarise the monitoring locations which were unavailable within each of the three batches. This is typically due to SD card data corruption.

Table 25: Batch 1 unavailable monitoring locations

<table>
<thead>
<tr>
<th>Ring ID</th>
<th>Primary Substation Name</th>
<th>Secondary Substation Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>037</td>
<td>Chassen Rd</td>
<td>Ambleside Road</td>
</tr>
<tr>
<td>080</td>
<td>Green Ln</td>
<td>Tithebarn Road</td>
</tr>
<tr>
<td>104</td>
<td>Hyde</td>
<td>Pumping Station</td>
</tr>
<tr>
<td>116</td>
<td>Levenshulme</td>
<td>Mosley Road</td>
</tr>
<tr>
<td>123</td>
<td>Monton</td>
<td>Albert Street</td>
</tr>
<tr>
<td>123</td>
<td>Monton</td>
<td>Vicars Street</td>
</tr>
</tbody>
</table>

Table 26: Batch 2 unavailable monitoring locations

<table>
<thead>
<tr>
<th>Ring ID</th>
<th>Primary Substation Name</th>
<th>Secondary Substation Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>031</td>
<td>Castleton</td>
<td>Castleton Hsg</td>
</tr>
<tr>
<td>031</td>
<td>Castleton</td>
<td>O'Neil's</td>
</tr>
<tr>
<td>047</td>
<td>Clover Hill</td>
<td>Avondale Rd</td>
</tr>
<tr>
<td>058</td>
<td>Dickinson St</td>
<td>George Street</td>
</tr>
<tr>
<td>058</td>
<td>Dickinson St</td>
<td>Tuscany House</td>
</tr>
<tr>
<td>063</td>
<td>Droylsden East</td>
<td>Water Lane</td>
</tr>
<tr>
<td>072</td>
<td>Farnworth</td>
<td>Primrose Street</td>
</tr>
<tr>
<td>072</td>
<td>Farnworth</td>
<td>Roosevelt Road</td>
</tr>
<tr>
<td>099</td>
<td>Higher Mill</td>
<td>Gatlley Road (No. 90)</td>
</tr>
<tr>
<td>114</td>
<td>Levenshulme</td>
<td>Cliftona Works</td>
</tr>
<tr>
<td>114</td>
<td>Levenshulme</td>
<td>Fairbourse Road</td>
</tr>
<tr>
<td>149</td>
<td>Roman Road</td>
<td>Abbotsford Avenue</td>
</tr>
<tr>
<td>149</td>
<td>Roman Road</td>
<td>Longshaw Mill</td>
</tr>
</tbody>
</table>
The data directory structure for several monitoring locations in Batch 1 had to be manually reorganised to use a consistent format; this is necessary to facilitate automated analyses of the data. Furthermore, the data from the “Hibson Road” monitoring location from the “Clover Hill” ring circuit is missing weekly trend data within Batch 1.

**G.2.3 Over-triggering**

There are several instances where the measured load current is close to or greater than the maximum Rogowski coil current sensor rating (500 A). This causes the “Phase Current Trigger” function of each PQube to continuously activate because the default threshold is 500 A. For each activation event, the three-phase voltage and current waveforms are sampled and detailed RMS information is captured.

The PQube devices are unable to cope with continued triggering and, after a period of time, the devices fail to correctly capture any further events. Therefore, the measurement locations which accrue large amounts of data may be partially unusable.

This problem of “over-triggering” can be detected by searching the PQube data for “*.dat” files. These are temporary binary files which each PQube should use to generate the final data output formats (i.e., CSV, PQDIF, and image files). The presence of some “*.dat” files is normal, but an excessive number suggests that over-triggering has occurred. However, in some cases the CSV files for weekly trends are generated correctly despite over-triggering. Table 28 summarises the occurrences in each batch of data, with the worst cases highlighted in red.

---

<table>
<thead>
<tr>
<th>Ring ID</th>
<th>Primary Substation Name</th>
<th>Secondary Substation Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>047</td>
<td>Clover Hill</td>
<td>Avondale Rd</td>
</tr>
<tr>
<td>058</td>
<td>Dickinson St</td>
<td>Abbey National</td>
</tr>
<tr>
<td>058</td>
<td>Dickinson St</td>
<td>George Street</td>
</tr>
<tr>
<td>058</td>
<td>Dickinson St</td>
<td>Manchester Town Hall</td>
</tr>
<tr>
<td>058</td>
<td>Dickinson St</td>
<td>Nicholas Street</td>
</tr>
<tr>
<td>058</td>
<td>Dickinson St</td>
<td>The Art House</td>
</tr>
<tr>
<td>063</td>
<td>Droylsden East</td>
<td>Water Lane</td>
</tr>
<tr>
<td>085</td>
<td>Greenhill</td>
<td>Lees Brook Mill</td>
</tr>
<tr>
<td>088</td>
<td>Griffin</td>
<td>Revidge Road</td>
</tr>
<tr>
<td>104</td>
<td>Hyde</td>
<td>Pumping Station</td>
</tr>
<tr>
<td>106</td>
<td>Hyndburn Rd</td>
<td>Booth Street</td>
</tr>
<tr>
<td>116</td>
<td>Levenshulme</td>
<td>Crossley Road</td>
</tr>
<tr>
<td>116</td>
<td>Levenshulme</td>
<td>Mosley Road</td>
</tr>
<tr>
<td>152</td>
<td>Royton</td>
<td>Fir Lane Estate</td>
</tr>
<tr>
<td>153</td>
<td>Sale</td>
<td>Temple Road N</td>
</tr>
<tr>
<td>176</td>
<td>Whalley Range</td>
<td>Ryebank Road</td>
</tr>
<tr>
<td>176</td>
<td>Whalley Range</td>
<td>Wood Road</td>
</tr>
</tbody>
</table>

**Table 27: Batch 3 unavailable monitoring locations**
<table>
<thead>
<tr>
<th>Ring ID</th>
<th>Primary Substation Name</th>
<th>Secondary Substation Name</th>
<th>Batch 1: Number of *.dat Files</th>
<th>Batch 2: Number of *.dat Files</th>
<th>Batch 3: Number of *.dat Files</th>
</tr>
</thead>
<tbody>
<tr>
<td>003</td>
<td>Ashton On Mersey</td>
<td>Magnolia Close</td>
<td>1726</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>031</td>
<td>Castleton</td>
<td>Castleton Hsg</td>
<td>12</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>036</td>
<td>Chamberhall</td>
<td>Arley Ave</td>
<td>34118</td>
<td>47382</td>
<td>0</td>
</tr>
<tr>
<td>037</td>
<td>Chassen Rd</td>
<td>Hastings Drive</td>
<td>926</td>
<td>616</td>
<td>0</td>
</tr>
<tr>
<td>038</td>
<td>Chatsworth Street</td>
<td>Ramsden Special School</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>047</td>
<td>Clover Hill</td>
<td>Avondale Road</td>
<td>71359</td>
<td>54493</td>
<td>0</td>
</tr>
<tr>
<td>056</td>
<td>Denton East</td>
<td>Ruskin Ave</td>
<td>11</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>056</td>
<td>Denton East</td>
<td>Scott Road</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>058</td>
<td>Dickinson St</td>
<td>George Street</td>
<td>14</td>
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<td>0</td>
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<tr>
<td>058</td>
<td>Dickinson St</td>
<td>Nicholas Street</td>
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<td>058</td>
<td>Dickinson St</td>
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<td>3</td>
<td>0</td>
</tr>
<tr>
<td>058</td>
<td>Dickinson St</td>
<td>Manchester Town Hall</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>058</td>
<td>Dickinson St</td>
<td>Tuscany House</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>063</td>
<td>Droylesden East</td>
<td>Old Fm Crescent</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>069</td>
<td>Exchange St</td>
<td>Harwood Street</td>
<td>8</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>072</td>
<td>Farnworth</td>
<td>Primrose Street</td>
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<td>0</td>
<td>6</td>
</tr>
<tr>
<td>072</td>
<td>Farnworth</td>
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<td>0</td>
<td>0</td>
<td>26</td>
</tr>
<tr>
<td>078</td>
<td>Great Harwood</td>
<td>Delph Mill</td>
<td>25</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>078</td>
<td>Great Harwood</td>
<td>Mount Street</td>
<td>0</td>
<td>1220</td>
<td>0</td>
</tr>
<tr>
<td>080</td>
<td>Green Ln</td>
<td>Delaheys Road</td>
<td>41169</td>
<td>0</td>
<td>56</td>
</tr>
<tr>
<td>080</td>
<td>Green Ln</td>
<td>Tithebarn Road</td>
<td>0</td>
<td>2582</td>
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<tr>
<td>085</td>
<td>Greenhill</td>
<td>Lees Brook Mill</td>
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<td>40343</td>
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<tr>
<td>085</td>
<td>Greenhill</td>
<td>Woodend</td>
<td>0</td>
<td>3287</td>
<td>0</td>
</tr>
<tr>
<td>088</td>
<td>Griffin</td>
<td>Revidge Road</td>
<td>0</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>096</td>
<td>Heywood</td>
<td>Hopwood Rec</td>
<td>41161</td>
<td>4835</td>
<td>0</td>
</tr>
<tr>
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<td>Heywood</td>
<td>Glamis Avenue</td>
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<td>0</td>
<td>2</td>
</tr>
<tr>
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<td>Higher Mill</td>
<td>Gatley Road</td>
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<td>2840</td>
<td>12282</td>
</tr>
<tr>
<td>099</td>
<td>Higher Mill</td>
<td>Gatley Road (No. 90)</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>101</td>
<td>Holme Road</td>
<td>Mulberry Avenue</td>
<td>0</td>
<td>6</td>
<td>3787</td>
</tr>
<tr>
<td>101</td>
<td>Holme Road</td>
<td>Whitefield Road</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>106</td>
<td>Hyndburn Road</td>
<td>Booth Street</td>
<td>0</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>114</td>
<td>Levenshulme</td>
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<td>58239</td>
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<td>0</td>
</tr>
<tr>
<td>114</td>
<td>Levenshulme</td>
<td>Fairbourne Road</td>
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<td>0</td>
<td>14</td>
</tr>
<tr>
<td>116</td>
<td>Levenshulme</td>
<td>Crossley Road</td>
<td>0</td>
<td>1914</td>
<td>0</td>
</tr>
<tr>
<td>116</td>
<td>Levenshulme</td>
<td>Mosley Road</td>
<td>0</td>
<td>1506</td>
<td>0</td>
</tr>
<tr>
<td>121</td>
<td>Middleton Junction</td>
<td>Green Street</td>
<td>0</td>
<td>3</td>
<td>0</td>
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<tr>
<td>121</td>
<td>Middleton Junction</td>
<td>Mills Hill Sec School</td>
<td>52959</td>
<td>2966</td>
<td>0</td>
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<tr>
<td>123</td>
<td>Monton</td>
<td>Albert Street</td>
<td>0</td>
<td>1035</td>
<td>87963</td>
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<td>128</td>
<td>Moss Nook</td>
<td>Dawson Road</td>
<td>7300</td>
<td>2093</td>
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<tr>
<td>131</td>
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<td>Oakwood Drive</td>
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<td>6</td>
</tr>
<tr>
<td>131</td>
<td>Musgrave Rd</td>
<td>Stapleton Ave</td>
<td>8</td>
<td>25</td>
<td>8</td>
</tr>
<tr>
<td>147</td>
<td>Reddish Vale</td>
<td>Goldsmith Road</td>
<td>17</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Ring ID</td>
<td>Primary Substation Name</td>
<td>Secondary Substation Name</td>
<td>Batch 1: Number of *.dat Files</td>
<td>Batch 2: Number of *.dat Files</td>
<td>Batch 3: Number of *.dat Files</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------</td>
<td>---------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>147</td>
<td>Reddish Vale</td>
<td>Lindfield Road</td>
<td>18</td>
<td>9082</td>
<td>0</td>
</tr>
<tr>
<td>149</td>
<td>Roman Rd</td>
<td>Abbotsford Ave</td>
<td>10</td>
<td>0</td>
<td>10235</td>
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<tr>
<td>152</td>
<td>Royton</td>
<td>Fir Lane Estate</td>
<td>0</td>
<td>3</td>
<td>0</td>
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<tr>
<td>152</td>
<td>Royton</td>
<td>Oozewood Road</td>
<td>2425</td>
<td>96171</td>
<td>0</td>
</tr>
<tr>
<td>153</td>
<td>Sale</td>
<td>Dane Mornington</td>
<td>2</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>153</td>
<td>Sale</td>
<td>Temple Road N</td>
<td>56472</td>
<td>5160</td>
<td>0</td>
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<td>156</td>
<td>South East Macc</td>
<td>Heapy Street</td>
<td>0</td>
<td>260</td>
<td>0</td>
</tr>
<tr>
<td>156</td>
<td>South East Macc</td>
<td>The Wharf</td>
<td>0</td>
<td>3775</td>
<td>0</td>
</tr>
<tr>
<td>161</td>
<td>Spa Road</td>
<td>Kays Hanover Street</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>161</td>
<td>Spa Road</td>
<td>Kent Street</td>
<td>0</td>
<td>68</td>
<td>0</td>
</tr>
<tr>
<td>164</td>
<td>St Annes</td>
<td>Klinhouse Estate</td>
<td>1107</td>
<td>5215</td>
<td>0</td>
</tr>
<tr>
<td>176</td>
<td>Whalley Range</td>
<td>Ryebank Road</td>
<td>334</td>
<td>25573</td>
<td>0</td>
</tr>
<tr>
<td>176</td>
<td>Whalley Range</td>
<td>Wood Road</td>
<td>836</td>
<td>1726</td>
<td>0</td>
</tr>
<tr>
<td>180</td>
<td>Woodley</td>
<td>Middlesex Road</td>
<td>0</td>
<td>109851</td>
<td>0</td>
</tr>
<tr>
<td>180</td>
<td>Woodley</td>
<td>Travellers Call</td>
<td>0</td>
<td>316</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 28: Measurement locations with evidence of over-triggering

This issue has been raised with PQube manufacturer, Power Standards Lab (PSL). PSL has acknowledged that when there are excessive back-to-back events (within seconds apart), the PQube processor may time-out. As a result, the PQube will reset and some data will not be captured. Therefore, following receipt of the Batch 1 data and the identification of this issue, it has been necessary to change the triggering configuration for the relevant PQube devices to prevent further over-triggering. A new current threshold setting of 1000 A, based on analysis of existing (healthy) demand data, has been selected. An updated PQube configuration file has been provided to ENWL on 11th March 2014. The generation of images and PQDIF files has also been disabled in the PQube configuration to facilitate copying data from each SD card after collection. It can be observed from the Batch 3 data in Table 28 that the use of the updated configuration file has significantly reduced the occurrences of over-triggering.
G.3 Merging data from multiple batches

To extract data from a PQube monitoring device, the SD card must be removed and swapped with a new SD card. The new SD card must contain the same PQube configuration setting file as used for all PQube devices in the C2C trial.

Due to the process of swapping SD cards, it is inevitable that there will be a break in the data capture while an SD card is swapped. However, the data from all batches must be merged for performing power quality analyses, and the merging can be achieved in the following ways:

1. Copy all directories for each batch into a single master directory. However, the new batch of data will contain a new CSV file for each trend type (monthly, weekly, and daily) which is likely to overlap with the corresponding CSV file for the same date from the previous batch. This issue can be mitigated in the following ways:
   a. Overwrite duplicate files with either the older or the newer file. This will result in some data loss, in addition to the time required to swap the SD card, from the partial data in the overwritten file.
   b. Keep both files, with the newer file being assigned a new filename.
   c. Merge each pair of overlapping CSV files together into a single file. This could be automated (which is potentially very complex) or done manually (which would be very time-consuming).

2. Maintain a separate directory tree structure for each batch of data. A data “scanning” process must be applied to each batch, with data appended to a master database. After all batches have been added to the database, power quality analyses can be conducted.

For each of the above options, the original monitoring data must be maintained in a consistent format, e.g., directories representing each monitoring location must be named consistently across each batch of data. Option 2 has been selected to eliminate the possibility of data loss and to minimise implementation complexity. The full implementation is documented in Section G.6.

The output of the merging process is visualised in Figure 83 (with a detailed section shown in Figure 84), for the aggregate of Batches 1, 2, and 3. Each green-shaded bar represents the presence of monitoring data for a given location, on a day-by-day basis. If a bar is shaded red, where the quantity of data is less that the “nominal” value, then daily data are missing. This is typically due to event “over-triggering” causing the PQube to reset, such as can be seen for the “Ashton On Mersey, Magnolia Close” and “Clover Hill, Avondale Road” monitoring locations, with reference to Table 28. Missing data could also be due to a failure of the power supply to the PQube device after installation, such as a blown fuse, or due to a genuine circuit outage. Blue lines indicate the date when a new batch of data starts and these dates typically coincide with a partial loss of daily data due to the processes of swapping SD cards.
Figure 83: Daily data availability
Figure 84: Detailed section of Figure 83
G.4 Validating time synchronisation

G.4.1 Overview of approach

Each PQube records the average system frequency measurement in 5-minute intervals, within the weekly trend data. During normal system conditions, frequency measurements should be the same at all locations throughout the UK power system. Therefore, trends in measured system frequency can be used to synchronise the local clock of each measurement device. A simplified example is shown in Figure 85, where the clock time offset, $\Delta t$, exhibited by Monitor 3 can be corrected by comparison with the measured frequency trends from Monitor 1 and Monitor 2.

![Simplified overview of frequency trend synchronisation](image)

Figure 85: Simplified overview of frequency trend synchronisation

Figure 86 illustrates a selection of frequency measurements starting from 1st April 2013, where each coloured column represents a 5-minute period. The entire distribution of frequency measurements is colour-coded between red (relatively low frequency) and green (relatively high frequency). Row 3 contains similar measurements of the National Grid system frequency, obtained from GridWatch [25]; the timestamps for both sources of data have been aligned.
In the majority of cases, the PQube frequency measurements are well-correlated—both with each other, and with the third-party system frequency measurement. This is indicated by each column being approximately the same colour, and this pattern is consistent across the full time range within the Batch 1 data. Therefore, this confirms that the PQube internal clocks have been set correctly and are reliable within approximately 5 minutes. This is sufficiently accurate for the power quality analysis tasks described in Chapter 6.

In some cases, such as rows 4 and 5 in Figure 86, the frequency measurement is not consistently aligned. It is possible to automate this method of clock validation for the each PQube, and to thereby automatically correct the timestamps for these six locations. This method is described in the following section.

G.4.2 Generic time synchronisation detection

The process described in Section G.4.1 has been automated in software. By assuming that, at a given instant in time, the majority of PQube devices retain
accurate clocks, it is possible to correlate the frequency measurements from a single PQube device with the mean value across all PQube devices. The third-party measurement data from GridWatch cannot be used as a reference because substantial sections of data during the C2C trial are missing, and the sampling period is not reliable.

If the frequency measurement for device \( i \) out of \( n \) at time \( t \) is \( f_{i,t} \), the mean frequency measurement from all devices at time \( t \) is \( m_t \):

\[
m_t = \frac{\sum_{i=1}^{n} f_{i,t}}{n}
\]

In other words, \( m_t \) is the mean of each column of frequency measurements as shown in Figure 86. Therefore, vectors of all PQube frequency measurements and the corresponding mean values within a window size, \( w \), can be calculated:

\[
F_i = [f_{i,1} \ldots f_{i,w}]
\]

\[
M = [m_1 \ldots m_w]
\]

A window size of 1 day (\( w = 288 \) samples for 5-minute sampling) has been used. The correlation coefficient \([26], \rho, \) between the 288 frequency measurements for a given PQube device and the 288 mean values can be calculated as follows, where \( \bar{X} \) is the mean of vector \( X \), and \( \sigma_X \) is the standard deviation of \( X \):

\[
\rho(F_i, M) = \frac{\sum_{t=1}^{w} (F_{i,t} - \bar{F}_i)(M_t - \bar{M})}{(w - 1)\sigma_{F_i}\sigma_M} = \frac{\sum_{t=1}^{w} (F_{i,t} - \bar{F}_i)(M_t - \bar{M})}{\sqrt{\sum_{t=1}^{w} (F_{i,t} - \bar{F}_i)^2} \sqrt{\sum_{t=1}^{w} (M_t - \bar{M})^2}}
\]

A correlation coefficient value of \( \rho(F_i, M) = 1.0 \) signifies that the two frequency trends are fully positively linearly correlated. A threshold of \( \rho(F_i, M) > 0.9 \) has been used to determine the condition for PQube \( i \) being sufficiently correlated with the mean such that the clock of PQube \( i \) can be trusted. The output of this process is a day-by-day assessment of the “trustworthiness” of the clock for each PQube. Data from at least 20 monitoring locations must be available for each window before the time synchronisation detection process is attempted.

**G.4.3 Automatically correcting time offsets**

As noted in Section G.4.1, the measured frequency trends for several PQube devices do not correlate with the other measurements, implying that these PQube clocks have not been set consistently. It is possible to correct the clocks for these devices by detecting the clock offset. This can be achieved by sliding the window of frequency measurements, as described in Section G.4.2, backwards or forwards in time until the correlation threshold is met. I.e., the window used for calculating \( F_i \) is adjusted, while \( M \) is held constant.

A 5-minute sampling period is used in the weekly trend data and therefore the increment for sliding the window is 5 minutes. A limit has been established if the
clock offset is not found within ±48 hours. This process is computationally intensive, so the results are cached in a data file to facilitate later analysis work.

G.4.4 Results

Figure 87 visualises the initial results from the time synchronisation process, before calculating and including clock offsets. Green shaded areas indicate that the correlation coefficient is greater than the selected threshold value and that the PQube clock is therefore “trusted”; red shaded areas indicate that the correlation coefficient does not exceed the threshold. It can be observed that all the correlation coefficient values drop below the threshold during the change from Batch 1 to Batch 2. This is due to a higher proportion of the PQube devices’ clocks having a time offset, which thereby distorts the mean frequency values which are calculated as described in Section G.4.2 and which are used as the reference for the correlation.
Figure 87: Initial time synchronisation results (without clock offset correction)

The time synchronisation process can be significantly improved by catering for individual PQube clock offsets, as illustrated in Figure 88. All periods with a low correlation coefficient (the red-shaded areas) are thereby eliminated. The majority of the remaining periods where the time synchronisation is not valid are due to missing data. In general, the PQube clocks are typically off by one hour, most likely due to
the clock being manually set during British Summer Time (BST), when it should have been set according to Coordinated Universal Time (UTC) or Greenwich Mean Time (GMT).

![Figure 88: Time synchronisation results with clock offset correction](image)
A further improvement can be obtained by assuming that relatively short gaps in time synchronisation validity, between periods which have been validated, can also be “trusted”. The results, for a maximum gap duration of one week, are shown in Figure 89.
G.5 Evaluation of NOP state changes

The power quality analysis process, as documented in Chapter 6, requires one week of monitoring data before and one week after an NOP state change on a C2C ring circuit. The NOP state should not change during this period. This ensures that weekly demand trends are captured, so that there is reasonable confidence that the two week-long periods being compared are consistent, except for the state of the NOP. Ideally, monitoring data should be available from both of the monitoring locations closest to the NOP on each ring circuit.

Figure 90 summarises the process of using the NOP log, provided by ENWL and containing the NOP state change events for all C2C trial circuits, with the monitoring data to determine which NOP state changes are valid for power quality analysis.

| Stage 1 | Detect NOP state change events in NOP log |
| Stage 2 | Determine which NOP state change events are valid, i.e., over two weeks |
| Stage 3 | Find monitoring locations with data for week before and after each NOP event |
| Stage 4 | Verify that continuous data are available from each monitoring location, i.e., no missing values |
| Stage 5 | Verify PQube clock synchronisation, using measured frequency correlation |
| Stage 6 | Verify that demand does not vary significantly between each week |

The results of the process described in Figure 90 are given in Table 29. Overall, 52 NOP state change events are valid for power quality analysis, and this includes data from a total of 34 unique monitoring locations across 23 ring circuits. Overall, 2 potential events are eliminated due to invalid time synchronisation (comparing Stage 4 with Stage 5c in Table 29).
<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
<th>Number of NOP state change events</th>
<th>Number of monitoring locations</th>
<th>Number of ring circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Raw NOP state change events</td>
<td>1332</td>
<td>n/a</td>
<td>36</td>
</tr>
<tr>
<td>2</td>
<td>Events with valid date range</td>
<td>123</td>
<td>n/a</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>Monitoring data within date range</td>
<td>114</td>
<td>57</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>Continuous data available from at least one monitoring location on ring circuit</td>
<td>83</td>
<td>51</td>
<td>32</td>
</tr>
<tr>
<td>5a</td>
<td>After time synchronisation validation</td>
<td>77</td>
<td>47</td>
<td>30</td>
</tr>
<tr>
<td>5b</td>
<td>After time synchronisation validation, including clock offsets</td>
<td>78</td>
<td>49</td>
<td>31</td>
</tr>
<tr>
<td>5c</td>
<td>After time synchronisation validation, including offsets and additional “trusting”</td>
<td>81</td>
<td>49</td>
<td>31</td>
</tr>
<tr>
<td>6</td>
<td>After demand variation limitation</td>
<td>52</td>
<td>34</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 29: Summary of valid NOP events and monitoring data

The individual NOP state change events are visualised in Figure 91. Arrows indicate NOP state changes which are valid, i.e., where the NOP state is consistent for at least one week before and one week after the state change. The colour of the arrow represents the monitoring data which are available:

- **Red** arrows indicate that no monitoring locations are available, due to missing data or invalid time synchronisation.
- **Orange** arrows indicate that one monitoring location has valid data.
- **Green** arrows indicate that both monitoring locations have valid data.

The dark blue lines represent multiple NOP state changes occurring within a relatively short time.
There are 97 NOP state change events where one of the two week-long periods is slightly too short to qualify for the process given in Figure 90. This can be observed between March and June 2014 in Figure 91, and has been caused by scheduled NOP state changes being executed after approximately one week, rather than after at least one week. Figure 92 shows a histogram of the duration of time which is
“missing” for these NOP state change events. Approximately two-thirds of the events are missing two hours or less, so it may be possible to use these events to provide further analysis data (assuming that valid monitoring data are available for each event). Care must be taken to ensure that missing period of data is correctly mirrored in the “healthy” week to ensure consistent comparisons.

Figure 92: Histogram of NOP state changes which are slightly too short
G.6 Correlation of measurements between individual phases

Table 30 summarises inter-phase correlation coefficients for the mean measurement data for each valid NOP state change event (see Section G.4.2 for an explanation of the calculation). A value of 0.0 indicates no linear correlation between the two measurements. Values or 1.0 or -1.0 indicate positive or negative linear correlations, respectively.

<table>
<thead>
<tr>
<th>Phases</th>
<th>Demand</th>
<th>RMS Voltage</th>
<th>THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>A and B</td>
<td>0.79</td>
<td>0.91</td>
<td>0.96</td>
</tr>
<tr>
<td>B and C</td>
<td>0.85</td>
<td>0.92</td>
<td>0.94</td>
</tr>
<tr>
<td>C and A</td>
<td>0.81</td>
<td>0.90</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Table 30: Inter-phase correlation coefficients for Radial C2C operation

The results in Table 30 indicate that demand, RMS voltage, and THD are relatively highly positively correlated, i.e., trends in one phase are generally “followed” in the other two phases. Similar results are obtained for Interconnected C2C operation. This provides confidence that the measurement data are valid, and are not random data or excessively noisy.
G.7 Implementation

The implementation of the power quality monitoring processing is conducted in two steps:

1. Reading the raw PQube data files, which may be present for a number of different “batches”, and converting to a suitable format for later processing, as discussed in Section G.3. The power quality monitoring data are read from the raw format (CSV files) and stored in a hierarchical data format (HDF) using the Python “PyTables” library [27]. This has been selected for the following reasons:

   - Scalable to relatively large amounts of data.
   - Supports a Structured Query Language (SQL) style of queries on data.
   - Very fast query performance.
   - Supports compression to minimise the size of the database file and to improve query performance (compression reduces the size of disk reads, which generally improves overall performance).
   - Relational databases such as Oracle, SQL Server, and MySQL are not appropriate because relational features such as foreign keys are not required.

2. Validation and numerical analysis of the formatted monitoring data and comparison between Radial C₂C and Interconnected C₂C operation. This has been implemented using a Python script which accesses the previously-generated PyTables database file.
G.8 Overall Status of Power Quality Monitoring Data

This appendix has provided an assessment of the power quality monitoring data collected for the C2C project and has identified the instances where the monitoring data meet the criteria for the C2C power quality analysis work. At present, a total of 52 valid events have been identified for power quality analysis, and this represents a reasonable statistical sample size. The identification process is fully automated and can accommodate further batches of data as required during the remainder of the C2C project.

The issue of PQube devices “over-triggering” during normal load current conditions has affected several measurement locations and has disrupted data capture in some cases. However, action has been taken by ENWL to mitigate this problem by applying a different PQube configuration file.

The monitoring regime has also revealed that it is important that all scheduled NOP state changes within the C2C trial – if conducted for the purposes of generating data for power quality analysis – are executed with a consistent gap of at least one week before and one week after the event. Several events have been excluded from the analysis due to the lack of consistent gaps.

Following validation of the PQube clocks by analysing measured frequency, it is possible to confirm that the overall time synchronisation is excellent and, in general, will not impair the power quality analysis. Only two events have been excluded from power quality analysis due to uncertainty of the validity of PQube clocks.
References


