Analysis of Electrical Losses in Meshed Distribution System Operation

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Abstract

This paper describes the effects of meshed distribution system operation on network electrical losses, within the Capacity to Customers (C_2C) project led by Electricity North West. The losses have been computed for the circuits in configurations where the Normally Open Point is in both open and closed positions. This allows the benefits, from a losses perspective, of operation in a "closed ring" configuration to be quantified. The results generally illustrate that the benefits are marginal, but there are benefits to be gained. The data presented in this paper will be subsequently used by the University of Manchester to analyse the carbon and economic benefits of C_2C operation. This area of analysis will be extended to determine the annual aggregated power losses impact of C_2C operation by using annual half hourly load profile data.

1 Introduction

The Capacity to Customers (C_2C) project, led by Electricity North West in the UK, is funded via Ofgem's Low Carbon Networks Second Tier funding mechanism. C_2C was authorised to commence in January 2012 and is due to complete in December 2014. As the UK fulfils its decarbonisation obligations under the Climate Change Act 2008 to cut greenhouse gas emissions by 80% (of 1990 levels) by 2050, the demand on electricity networks is forecast to dramatically increase. This increase in electrical demand will be driven primarily through the decarbonisation of heat, transportation, and electricity production rather than by a growing population or growing energy usage. The likely consequences of this increase are ever greater electricity costs for customers and significant environmental and social impacts.

The aim of the C_2C project is to test new technology, network operational practices (i.e., operating with closed distribution rings), and commercial demand response contracts that will allow Electricity North West to increase the loadings on a selection of trial circuits representing approximately 10% of its 6.6/11 kV network – without resorting to conventional network reinforcement. In other words, the project will "release" inherent spare capacity in the 6.6/11 kV system in order to accommodate the future forecast increases in demand, whilst avoiding (or deferring) the cost and environmental impacts that are associated with traditional network reinforcement.

This paper presents the results of work carried out at the University of Strathclyde to model the losses associated with 34 of the circuits that have been selected for the C_2C trial. A simplified example that illustrates the method adopted, along with a more detailed overview of the methodology and a step-by-step description of the modelling and analysis processes, are presented. The full set of results for each of the 34 circuits is then presented, accompanied by discussion and analysis of results. The conclusion outlines the main findings and describes areas of activity that will be undertaken in the future.

2 Distribution Losses for C_2C Operation: Simplified Example

This section provides an overview of the theoretical impact that operating closed 6.6/11 kV rings – rather than conventional radial systems with Normally Open Points (NOPs) – may have upon distribution system losses. A simplified example ring circuit is given in Figure 1. A further simplified equivalent circuit representation is illustrated in Figure 2.

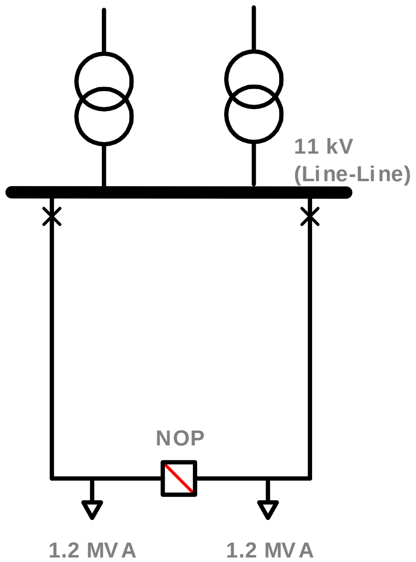

Figure 1: Example distribution system ring circuit

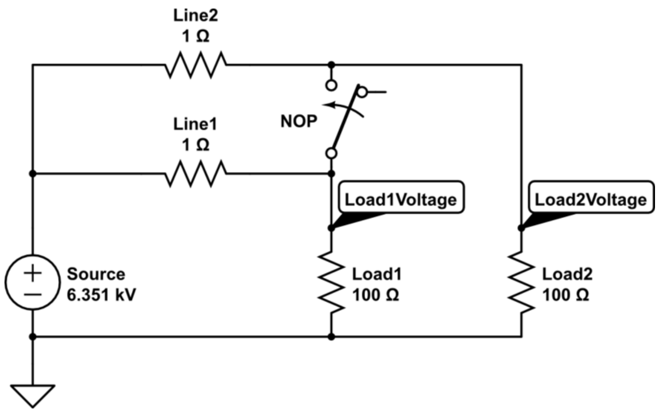

Figure 2: Simplified circuit representation

The effect of varying the resistance of Line 1 or Load 1 is provided in Table 1. The following can be concluded:

- If the two feeders are equally matched (i.e., the line resistances are equal, and the load resistances are equal), there is no difference in the total losses in the lines after closing the NOP. This is illustrated by scenario 1 in Table 1.
- When the line resistances are equal and then the NOP is closed, the current is shared (more or less) equally between the two lines, but the maximum line current is lower. Because the losses are proportional to   , the total losses are always less after closing the NOP. This is illustrated in scenarios 2 and 3 in Table 2.
- If the feeder resistances are not matched, then upon closing the NOP, one load voltage increases but the other decreases, as shown for scenarios 2-5 in Table 2. In each case, the total losses are always lower, as given in Table 1.

Scenario	Line 1	Line 2	Load 1	Load 2	Total Losses NOP Open	Total Losses NOP Closed
1	1 Ω	1 Ω	100 Ω	100 Ω	7.9 kW	7.9 kW
2	1 Ω	1 Ω	20 Ω	100 Ω	95.4 kW	69.8 kW
3	1 Ω	1 Ω	500 Ω	100 Ω	4.12 kW	2.93 kW
4	0.5 Ω	1 Ω	100 Ω	100 Ω	5.95 kW	5.35 kW
5	2 Ω	1 Ω	100 Ω	100 Ω	11.7 kW	10.5 kW

Table 1: Effect on losses for varying Load 1 resistance (green indicates an improvement)

	NOP Open				NOP Closed			
Scenario	Load 1 Voltage	Load 2 Voltage	Line 1 Current	Line 2 Current	Load 1 Voltage	Load 2 Voltage	Line 1 Current	Line 2 Current
1	6.29 kV	6.29 kV	62.9 A	62.9 A	6.29 kV	6.29 kV	62.9 A	62.9 A
2	6.05 kV	6.29 kV	302 A	62.9 A	6.16 kV	6.17 kV	190 A	179 A
3	6.34 kV	6.28 kV	62.9 A	12.7 A	6.31 kV	6.31 kV	36.7 A	39.1 A
4	6.32 kV	6.29 kV	63.2 A	62.9 A	6.31 kV	6.31 kV	82.8 A	43.4 A
5	6.23 kV	6.29 kV	62.3 A	62.9 A	6.27 kV	6.27 kV	42.5 A	82.9 A

Table 2: Effect on voltage and current (green indicates an improvement; red indicates an undesirable change)

The following assumptions apply in the simplified example:

- All loads are at the end of the feeders, which is representative of the worst case scenario for losses. In practice, loads will be distributed along the feeders.
- DC is assumed, so reactance is not considered.
- The switch representing the NOP has a resistance of 0.1 Ω when closed, to represent the additional line impedance. The losses in this resistance are included in Table 1 and Table 2.
- Constant-resistance loads are assumed, but similar results can be obtained with constant P, Q loads in a simulation package such as IPSA [1].

3 Methodology for Quantifying Electrical Losses

3.1 Overview

Figure 3 illustrates the overall process for analysing each ring circuit. The process is generic – it is applicable to all ring circuits used for the trial – and is fully automated. The following subsections describe each part of the analysis process in detail.

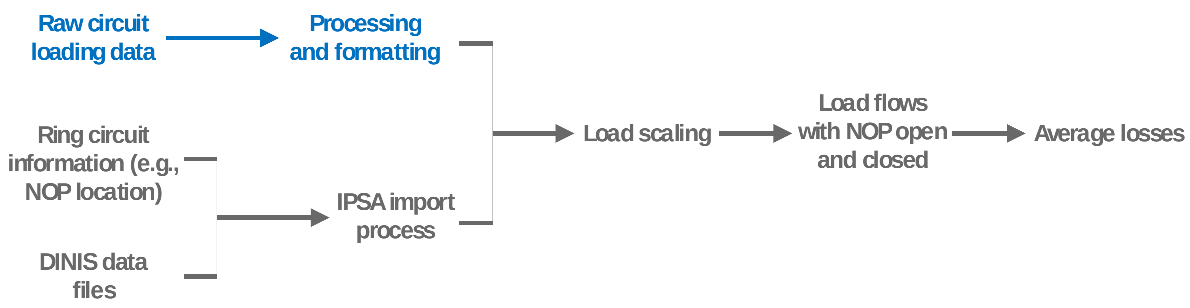

Figure 3: Overall circuit analysis process

3.2 Assumptions

The following assumptions have been used in this methodology:

1. Nominal line voltage, either 6.6 or 11 kV, is assumed at the primary busbar.
2. No Distributed Generation (DG) is included.
3. Load ratings for an entire feeder are scaled linearly. For simplicity, no load profiling has been performed.
4. The arithmetic mean of annual feeder current measurements is assumed to be an adequate estimate of average circuit loading conditions, and therefore can be used in the calculation of the average power losses and for extrapolation of annual energy losses.

   An alternative method involves calculating the load loss factor (LLF) from historical data and simulating each circuit at peak load; the average annual losses can then be calculated. This approach is not suitable for the scenarios where the NOP is closed, because the historical current measurements (which were measured with the NOP open) will be invalid.

3.3 Processing Circuit Loading Data

Real current measurements from the primary substations of each feeder, for the year 2012, have been used to determine circuit loading. Figure 4 illustrates the process of importing and processing the circuit loading data. 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.

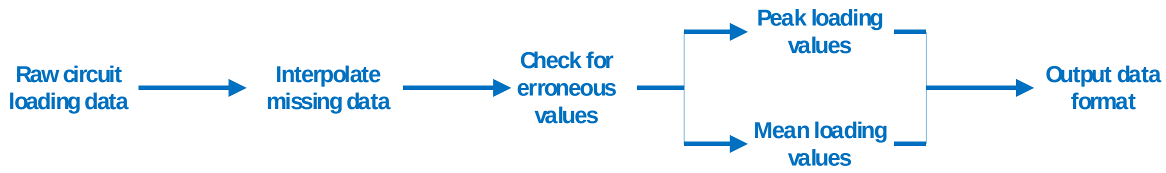

Figure 4: Importing and processing circuit loading data

In total, 5564 half-hourly RMS current measurement values (measured at the primary end of each feeder) are missing. This equates to 0.44% of the total number of values, or 1.61 days in aggregate. The reason for the missing data is due to failure of a Remote Terminal Unit (RTU) or an element within the communications system. Where possible, these missing values have been estimated by linear interpolation of the two adjacent half-hourly values.

Table 3 provides the output of the current measurement processing script. It can be observed that some peak current values are exceptionally high, which may be the result of erroneous data.

Measurement Location	Peak Current (A)	Mean Current (A)	Measurement Location	Peak Current (A)	Mean Current (A)
1001023CF05	194.2	99.7	2002053CW23	343.2	110.3
1001023CF09	344.3	83.0	3000093CW39	215.0	108.2
1001073CF05	262.2	141.7	3000093CW44	133.9	72.4
1001073CF16	307.6	46.2	3000154CF23	218.7	105.7
1001103CF04	135.3	68.4	3000154CF29	190.2	88.3
1001103CF13	410.4	80.2	3000243CW14	159.0	52.5
1001174CW05	380.7	87.9	3000243CW33	229.4	81.6
1001174CW10	151.9	39.0	3000613CW06	192.9	70.2
1001183CW10	311.5	141.9	3002383CW25	208.0	99.9
1001183CW11	174.9	82.5	3002383CW33	278.6	121.4
1001193CW05	484.8	60.2	3030234CW05	105.7	22.4
1001193CW08	334.7	167.3	3030234CW11	203.7	68.6
1001193CW13	134.4	66.3	3032154CW04	253.5	109.2
1001193CW14	236.8	125.2	3032154CW06	280.5	126.1
1001303CW07	182.8	102.7	3048813CW08	172.6	94.0
1001363CW03	179.7	92.2	3048813CW12	185.3	78.9
1001363CW11	859.0	84.0	4000023CF43	215.0	106.6
1001394CW02	120.7	58.1	4000023CF50	104.9	51.2
1001394CW10	154.0	60.4	4000063CF44	276.8	124.7
1006083CW04	210.5	102.9	4000063CF52	252.5	143.5
1006083CW13	255.2	127.2	4000073CW06	176.9	73.6
1006203CW04	245.3	124.1	4000073CW12	88.9	50.6
1006203CW11	212.0	108.5	4000083CW21	344.4	69.8
1006393CW02	133.6	52.8	4000083CW22	267.9	103.4
1006393CW11	84.2	41.7	4000133CF40	174.6	78.3
2001013CW12	293.3	93.3	4000133CF41	289.5	108.8
2001013CW19	262.5	97.2	4000513CF06	230.9	105.6
2001023CW12	246.2	107.5	4000513CF29	142.2	65.3
2001023CW17	248.8	58.1	4001113CF06	229.2	90.9
2001124CW13	193.2	48.8	4001113CF07	67.2	32.0
2001124CW14	249.8	101.4	4002084CW15	560.0	53.8
2001153CF12	275.1	142.4	4002084CW27	197.2	92.6
2001153CF21	380.8	39.2	6090034CW05	174.9	97.3
2001194CW01	193.4	114.5	6090034CW10	198.6	72.1
2001194CW09	96.2	53.5	1001303CW04	263.8	137.8
2002053CW14	246.9	111.4	3000613CW17	253.2	129.0

Table 3: Output from current measurement processing

3.4 Automatic Circuit Conversion

Electrical network data was available in the Distribution Network Information System (DINIS) format. IPSA has been used for modelling electrical losses because it can be readily scripted using the Python programming language. A template script (in Python) was used to import DINIS data files. This script has been significantly extended and modified to cater for the analysis of the electrical losses. For each circuit, the generated IPSA model has been manually verified by comparison with the authoritative network diagrams; this is required only once to ensure that the generic import process executes correctly.

The conversion script performs the following functions:

1. All DINIS data are converted to Python objects. A full IPSA representation of the DINIS data, which is geographically accurate, is created.
2. A graph of the network is created, as illustrated in Figure 5, 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.
3. The primary busbar is located using Dijkstra's algorithm [2] 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 detailed arrangement of many interconnected nodes within the DINIS data.
    a. Extraneous, "dangling" nodes are trimmed from the primary busbar.
    b. A node at the mid-point of the primary busbar nodes is selected, and a grid infeed IPSA component is connected to it. This node is set as the slack bus for IPSA load flows.
4. Starting from one of the secondary substations at the start of a feeder, a tree is built from the remaining nodes, using a depth-first search algorithm [3]. This is illustrated in Figure 6. 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.
5. For each of the two feeders in the ring circuit, the loads are iteratively scaled (up or down) and a load flow is performed. This process continues until the maximum feeder current equals either the peak or mean (depending on the results required) current measurement value from the data from the year 2012.
6. Two final load flows are performed: with the NOP open, and with the NOP closed. The total branch losses in each case are recorded.
7. The entire process is scripted to iterate through all 34 ring circuits automatically.

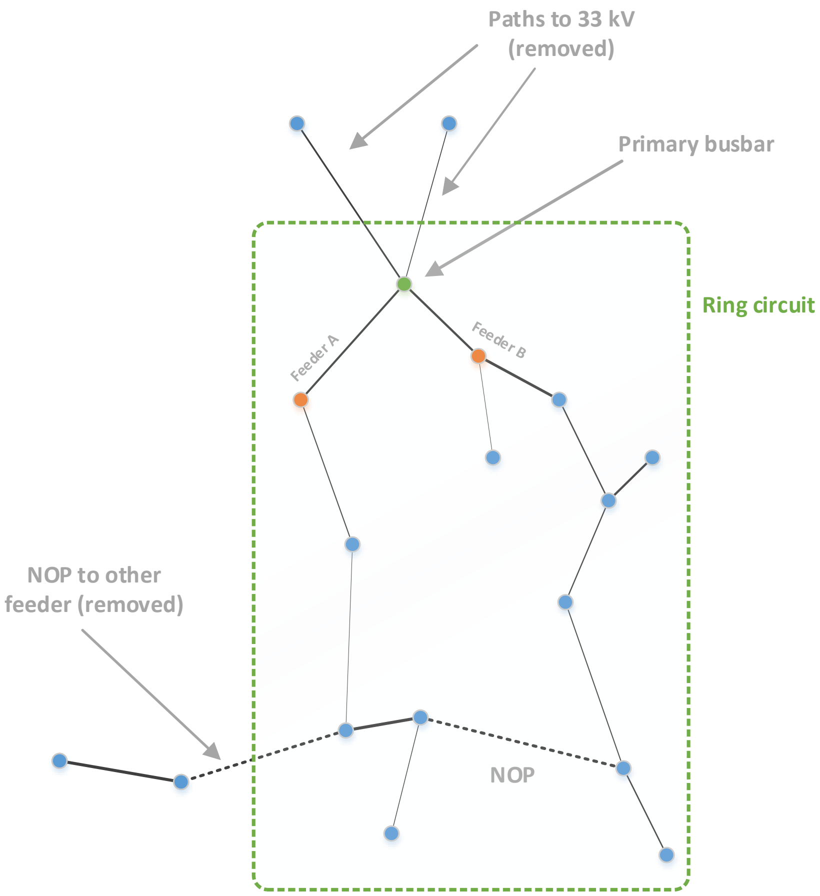

Figure 5: Ring circuit graph representation

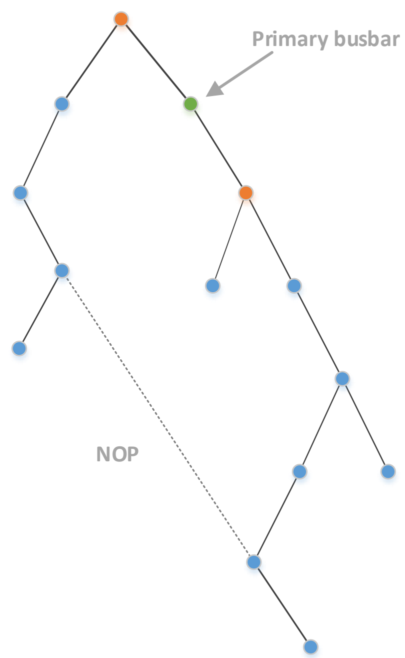

Figure 6: Ring circuit tree representation

4 Typical Circuit Data and Results

This section illustrates the analysis process in detail for a single ring circuit connected to the 6.6 kV Denton East primary substation, located east of Manchester, UK, as illustrated in Figure 7. The process is identical for all other circuits analysed. This ring circuit involves only cables (rather than overhead lines), and the loads are predominantly residential in nature.

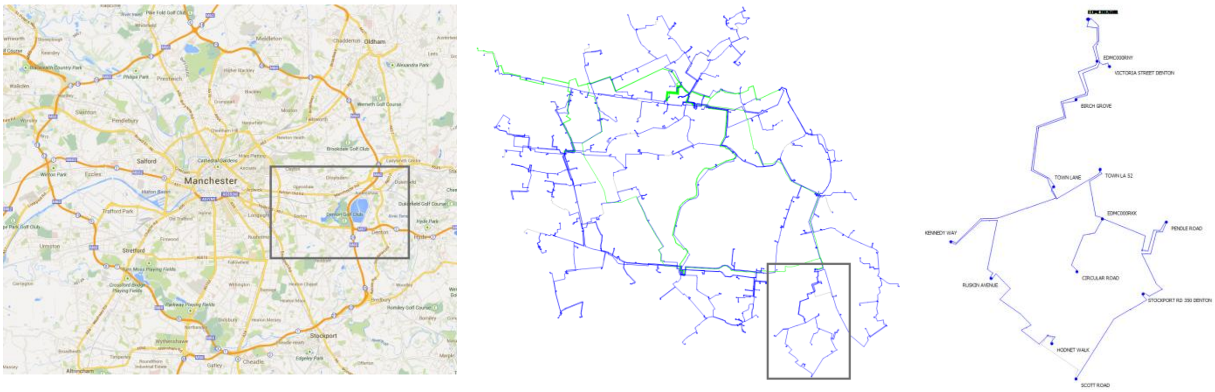

Figure 7: One circuit (out of 180) included in the trial

Figure 8 illustrates the simplified IPSA model containing only the ring circuit of interest. This model is generated automatically by the import script described in the previous section. The primary busbar and NOP are highlighted in Figure 8. Although not shown, there is a grid infeed at the primary busbar, and a constant PQ 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 with the original DINIS model, the primary busbar consists of several nodes, which are interconnected by zero-impedance lines.

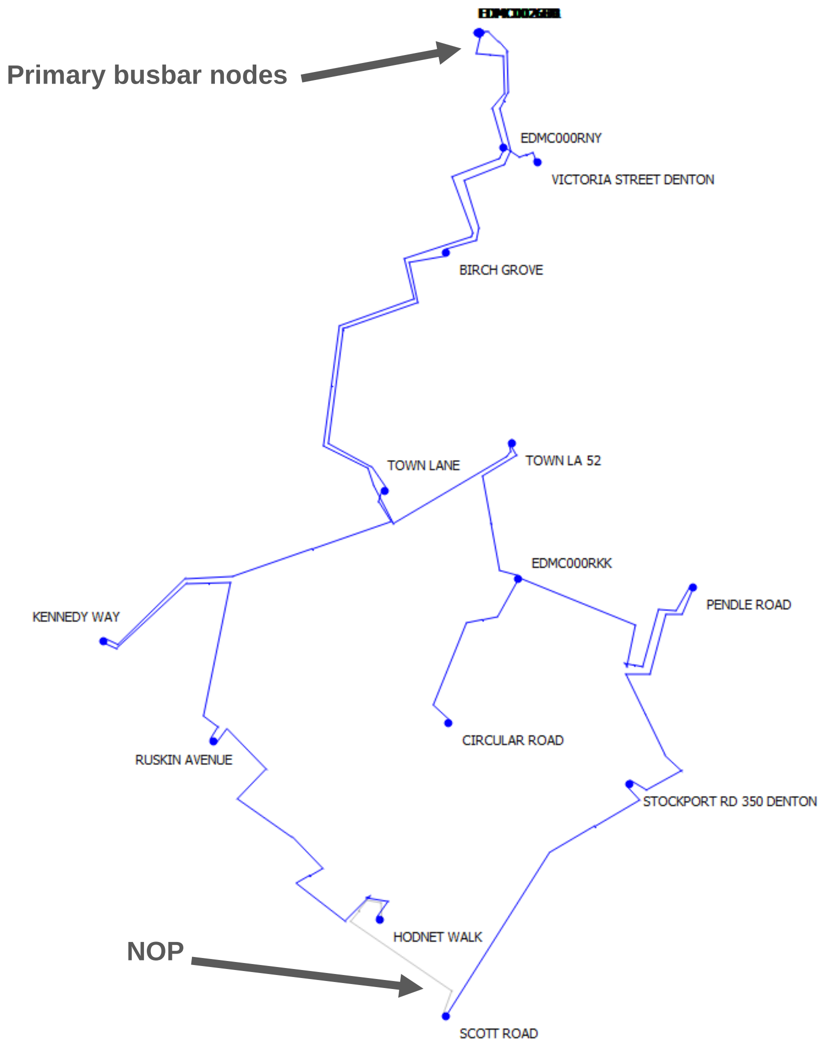

Figure 8: Ring circuit of interest at Denton East in IPSA

An example of daily demand for this ring circuit is shown in Figure 9, for 1st January 2012. Annual data are illustrated in Figure 10.

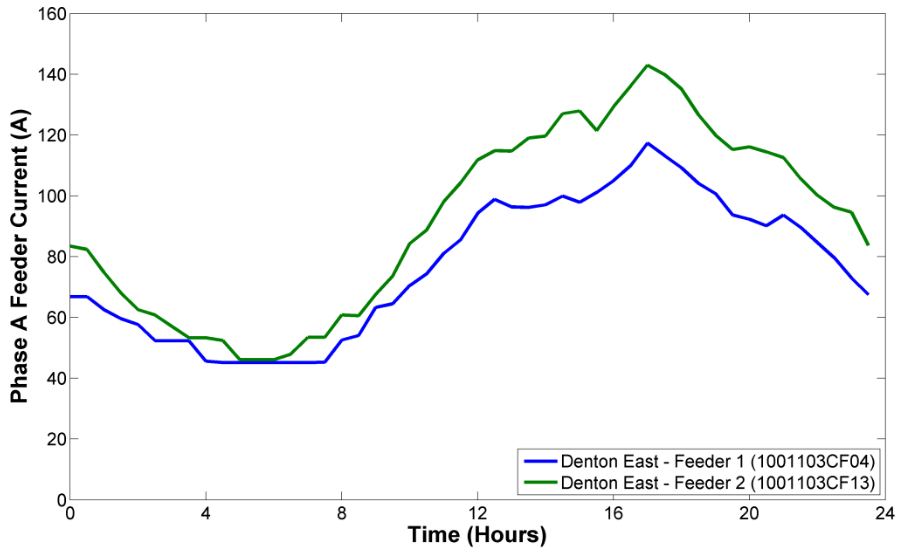

Figure 9: Half-hourly feeder current for Denton East primary, 1st January 2012

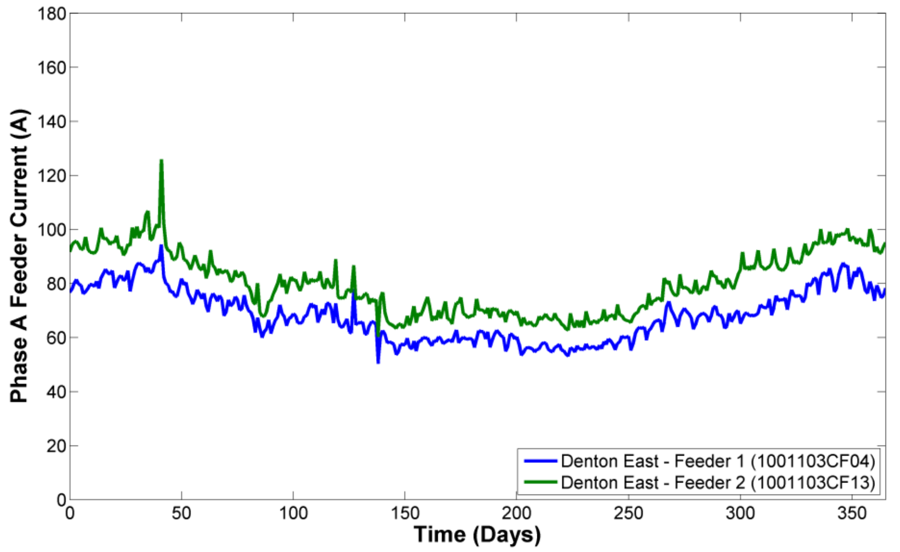

Figure 10: Daily mean feeder current for Denton East primary, for 2012

4.1 Results for Mean Loading

Figure 11 and Figure 12 illustrate load flows – at mean loading – with the NOP open and closed, respectively. The voltages at each node are also displayed, based on assumed nominal voltage at the primary. The red dots represent real power flow, and the blue dots represent reactive power exchanges.

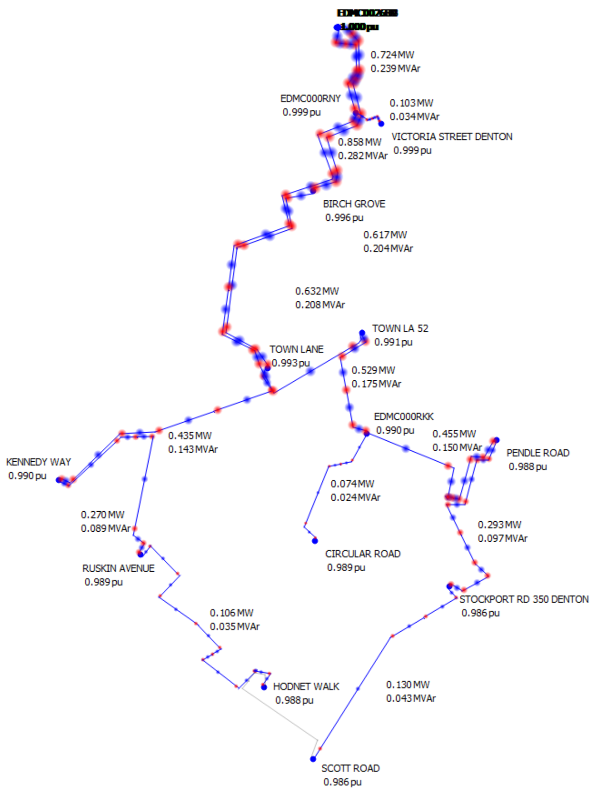

Figure 11: Load flow – NOP open, mean loading

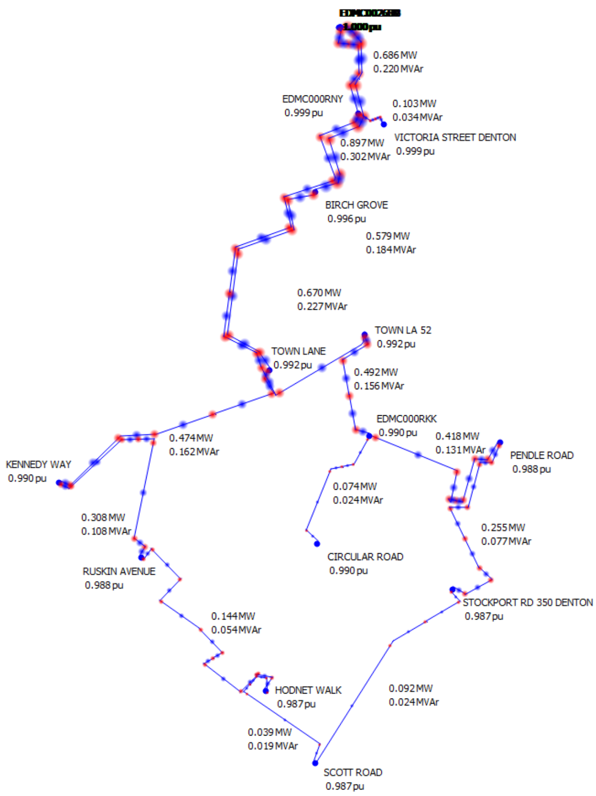

Figure 12: Load flow – NOP closed, mean loading

The total real power (   ) losses, as calculated by IPSA, and annual energy loss with the NOP open or closed are given in Table 4. The annual energy losses are calculated directly from the power losses at mean circuit loading.

	NOP Open	NOP Closed	Difference
Power losses	14.32 kW	14.13 kW	0.191 kW
Power losses (% of total power)	0.857 %	0.846 %	0.011 %
Annual energy loss	125.8 MWh	124.14 MWh	1.678 MWh

Table 4: Total power losses and annual energy loss, for mean loading

4.2 Results for Peak Loading

The load flow results at peak loading are of interest because it demonstrates the impact of C_2C when demand is increased, and allowing greater future demand on the network, without requiring reinforcement, is one of the main objectives and benefits of C_2C.

Figure 13 and Figure 14 illustrate load flows – at peak loading – with the NOP open and closed, respectively. At peak loading, the effect of closing the NOP on the voltage profile is more prominent. For example, the voltage at the Hodnet Walk substation is raised from 0.940 pu to 0.954 pu.

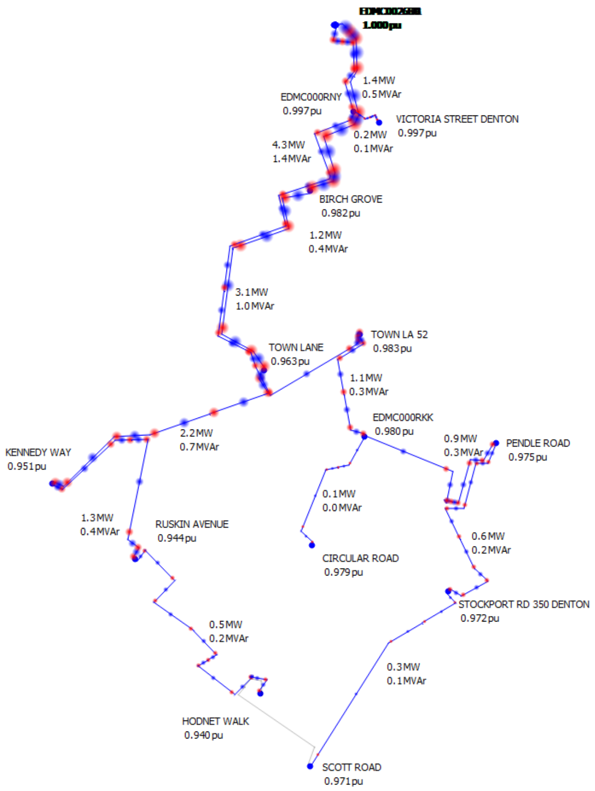

Figure 13: Load flow – NOP open, peak loading

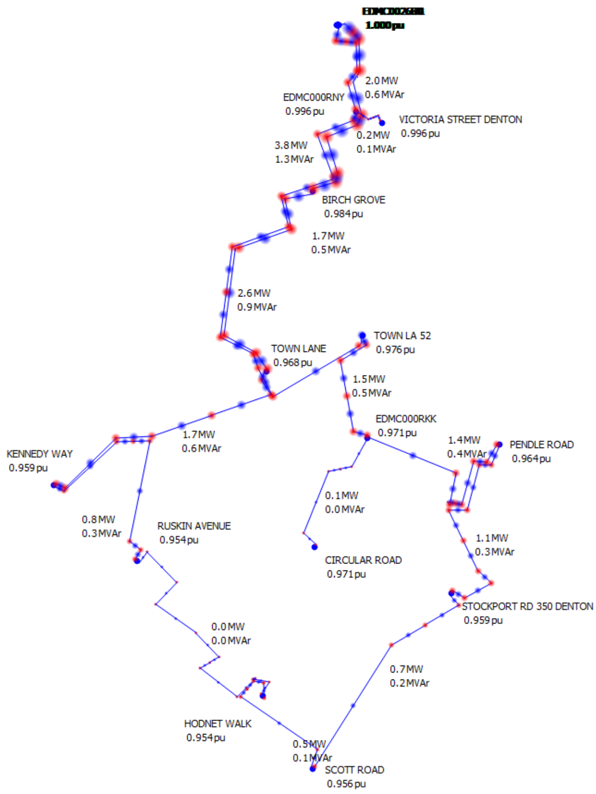

Figure 14: Load flow – NOP closed, peak loading

The total real power losses are given in Table 5.

	NOP Open	NOP Closed	Difference
Power losses	203.5 kW	185.7 kW	17.8 kW
Power losses (% of total power)	3.34 %	3.04 %	0.293 %

Table 5: Total power losses for peak loading

5 Full Results

Table 6 summarises the total distribution losses for each ring circuit, at mean loading, with the NOP open and closed. The losses have been provided as a mean instantaneous value, in kW, and as a percentage of the total apparent power supplied to the ring circuit from the primary substation. The total annual energy loss has also been estimated. Similarly, Table 7 provides the equivalent losses data at peak loading.

Primary Substation	NOP Open			NOP Closed		
	Total Losses (kW)	Total Losses (%)	Annual Energy Losses (MWh)	Total Losses (kW)	Total Losses (%)	Annual Energy Losses (MWh)
Ashton on Mersey	17.8	0.9	156.3	17.6	0.9	154.5
Castleton	23.1	1.2	203.1	16.4	0.8	143.8
Chamber Hall	34.0	1.4	298.9	36.2	1.5	318.1
Chassen Road	42.6	1.7	374.0	42.4	1.6	372.2
Chatsworth St	9.3	0.3	81.6	9.3	0.3	81.5
Clover Hill	24.7	1.3	216.7	24.1	1.2	211.4
Crown Lane	11.4	0.4	100.2	11.2	0.4	98.7
Denton East	14.2	0.9	125.2	14.1	0.8	124.1
Dickinson Street	1.6	0.2	14.5	1.4	0.1	12.4

Droylsden East	32.1	1.5	282.3	28.9	1.4	253.4
Exchange St	10.3	0.7	90.1	10.0	0.7	87.8
Farnworth	7.7	0.2	67.6	7.4	0.2	64.6
Great Harwood	15.4	0.8	134.9	15.1	0.8	132.8
Green Ln	7.6	0.3	66.6	5.0	0.2	43.6
Greenhill	17.3	1.2	152.4	16.0	1.1	140.1
Griffin	66.2	2.2	581.8	66.1	2.2	580.5
Heywood	35.2	1.8	309.4	25.6	1.3	225.3
Higher Mill	25.7	1.0	225.5	25.7	1.0	225.7
Holme Road	6.9	0.2	60.3	5.8	0.2	50.8
Hyde	19.8	0.9	173.9	18.0	0.8	158.5
Hyndburn Road	26.5	1.3	232.5	26.1	1.2	229.7
Levenshulme	8.2	0.6	71.8	7.9	0.6	69.1
Levenshulme 2	53.9	1.6	473.4	54.0	1.6	474.6
Middleton Junction	6.9	0.2	60.5	6.9	0.2	60.4
Moss Nook	2.7	0.1	24.0	2.7	0.1	24.0
Musgrave	14.9	0.7	130.9	14.7	0.7	129.4
Reddish Vale	36.4	1.5	319.9	36.3	1.5	319.2
Roman Rd	19.0	1.1	167.2	16.0	0.9	140.3
Royton	13.7	0.7	120.7	13.6	0.7	119.6
Sale	10.4	0.5	91.3	10.3	0.5	90.9
South East Macc 22	4.5	0.3	39.1	4.2	0.2	36.6
St Annes	17.3	1.3	151.9	12.3	0.9	108.4
Whalley Range	33.5	1.2	294.1	33.2	1.2	291.2
Woodley	16.9	0.4	148.1	16.4	0.4	144.0

Table 6: Summary of total circuit losses, at mean loading

Primary Substation	NOP Open		NOP Closed	
	Total Losses (kW)	Total Losses (%)	Total Losses (kW)	Total Losses (%)
Ashton on Mersey	169.2	2.8	148.2	2.5
Castleton	91.3	2.3	71.6	1.8
Chamber Hall	272.9	4.1	286.8	4.3
Chassen Road	172.4	3.3	172.2	3.3
Chatsworth St	34.4	0.6	34.4	0.6
Clover Hill	113.3	2.7	109.8	2.6
Crown Lane	99.7	1.2	99.4	1.2
Denton East	200.9	3.3	186.3	3.1
Dickinson Street	8.0	0.3	7.4	0.3
Droylsden East	218.7	3.5	217.4	3.5
Exchange St	49.7	1.6	49.8	1.7
Farnworth	22.5	0.4	21.7	0.4
Great Harwood	206.5	3.0	206.7	3.0
Green Ln	141.9	1.4	89.3	0.9
Greenhill	138.8	3.3	129.5	3.0
Griffin	281.4	4.8	280.6	4.8
Heywood	367.8	5.0	360.8	4.9
Higher Mill	118.1	2.2	118.2	2.2
Holme Road	177.6	1.2	174.1	1.2
Hyde	90.3	1.8	85.5	1.7
Hyndburn Road	170.9	3.3	171.1	3.3
Levenshulme	217.7	3.2	202.2	3.0
Levenshulme 2	202.7	3.2	203.4	3.2
Middleton Junction	30.2	0.4	30.1	0.4
Moss Nook	15.5	0.3	15.3	0.3
Musgrave	120.8	1.9	120.6	1.9
Reddish Vale	181.8	3.3	181.8	3.3
Roman Rd	76.9	2.1	64.3	1.8
Royton	51.1	1.3	50.6	1.3
Sale	692.8	5.9	524.5	4.6
South East Macc 22	42.9	0.7	41.6	0.7
St Annes	108.3	3.3	73.3	2.2
Whalley Range	115.0	2.3	113.0	2.3
Woodley	87.4	0.9	85.6	0.8

Table 7: Summary of total circuit losses, at peak loading

Table 8 highlights the difference in total losses that arises when the NOP is closed, for each ring circuit, i.e., the table summarises the effect of C_2C operation on distribution losses. Each data column is colour-coded to emphasis the relative improvement (or otherwise) to losses between circuits: green cells show the greatest improvement; red cells represent an increase in losses due to C_2C operation.

Primary Substation	Peak Loading	Mean Loading	
	Difference in Total Losses (kW)	Difference in Total Losses (kW)	Difference in Annual Energy Losses (MWh)
Ashton on Mersey	20.9	0.2	1.8
Castleton	19.7	6.8	59.3
Chamber Hall	-13.9	-2.2	-19.2
Chassen Road	0.2	0.2	1.8
Chatsworth St	0.0	0.0	0.1
Clover Hill	3.6	0.6	5.4
Crown Lane	0.3	0.2	1.6
Denton East	14.6	0.1	1.0
Dickinson Street	0.6	0.2	2.0
Droylsden East	1.3	3.3	28.8
Exchange St	-0.1	0.3	2.2
Farnworth	0.8	0.3	3.1
Great Harwood	-0.2	0.2	2.0
Green Ln	52.6	2.6	23.1
Greenhill	9.3	1.4	12.2
Griffin	0.8	0.1	1.3
Heywood	7.0	9.6	84.1
Higher Mill	-0.1	0.0	-0.2
Holme Road	3.5	1.1	9.5
Hyde	4.8	1.7	15.4
Hyndburn Road	-0.1	0.3	2.9
Levenshulme	15.5	0.3	2.7
Levenshulme 2	-0.8	-0.1	-1.2
Middleton Junction	0.1	0.0	0.1
Moss Nook	0.2	0.0	0.0
Musgrave	0.1	0.2	1.6
Reddish Vale	0.0	0.1	0.7
Roman Rd	12.6	3.1	26.9
Royton	0.5	0.1	1.1
Sale	168.3	0.0	0.4
South East Macc 22	1.3	0.3	2.5
St Annes	35.1	4.9	43.5
Whalley Range	1.9	0.3	2.8
Woodley	1.8	0.5	4.1

Table 8: The effect of C_2C operation on losses

6 Conclusions

This paper has presented a detailed description of the methodology used to calculate power losses and the results arising from the analyses of 34 circuits from C_2C operation. The results show that network losses are generally reduced, but the gains are marginal. This area of analysis will be extended to determine the annual aggregated power losses impact of C_2C operation by using annual half hourly load profile data. The University of Strathclyde will also during the project further analyse and disseminate the impact of C_2C operation with regard to available network capacity and a number of power quality metrics.

The data supplied within this paper will be used by the University of Manchester in order to calculate reductions in carbon emissions and the economic benefits associated with the C_2C project.

7 References

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