

Analysis and Quantification of the Benefits of Interconnected Distribution System Operation

Steven M. Blair, Campbell D. Booth, Paul Turner, and Victoria Turnham

Abstract—In the UK, the Capacity to Customers (C₂C) project is underway to determine the potential benefits of increased interconnection in distribution systems, combined with demand side response technology. Managed contracts with customers, i.e., the agreement that certain loads are interruptible following system faults, allows distribution circuits to be loaded beyond the limits presently required for security of supply. This potentially permits load growth but avoids the cost and environmental impact of conventional network reinforcement.

This paper provides the results of electrical system modelling to quantify the benefits of the C₂C operation, using actual circuit data and typical load distributions. Based upon simulations of these circuits, it is shown that increased interconnection generally leads to minor improvements in electrical losses and system voltage. By connecting managed (i.e., interruptible) loads, circuits typically can be loaded significantly further than the present practice in the UK—an average increase of 66% for radial operation and 74% for interconnected systems.

Index Terms—Automation and control, demand side response, distribution, interconnection, load flow.

I. INTRODUCTION

INCREASING electrical network interconnection is presently of interest for both transmission and distribution systems [1]. For distribution systems, interconnection offers several potential benefits, including: increased capacity for connecting load and generation, and therefore deferral or avoidance of network reinforcement costs; greater flexibility in the use of the available capacity; improved voltage profiles and voltage support; and reduced losses and voltage harmonic distortion due to lower system impedance. This is particularly relevant in the UK where 6.6 kV and 11 kV ring circuits, operating as two radial feeders, are common [2].

This paper quantifies the benefits of increased network interconnection, within the context of the Capacity to Customers (C₂C) project [3] presently being led by Electricity North West Limited in the UK. The project involves a consortium of ten industrial and academic partners. The aim of the C₂C Project is to test new technology, network operational practices (i.e., increased network interconnection), and commercial demand response contracts. These changes will allow the network operator 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. The project will thereby “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 focuses on the analysis of the effects of C₂C operation on electrical losses, the circuit voltage profile, and the available network capacity. This has been achieved using real system data for a representative proportion of the trial circuits.

II. PROJECT BACKGROUND

Fig. 1 provides a simplified overview of the aims of C₂C. Spare capacity—normally reserved for use during circuit outages when the system is operating in a reconfigured state, typically through a shift in the location of the normally-open point (NOP)—will be offered to new customers. This is possible due to a derogation from the normal requirements for security of supply in distribution networks in the UK, governed by Engineering Recommendation (ER) P2/6 [4]. By closing NOPs during normal system operation, additional loads with managed contracts for post-fault conditions can be connected: effectively sharing the capacity available from both radial feeders and avoiding or deferring the need for network reinforcement. The managed contracts permit the “C₂C loads” to be interrupted following fault conditions for a defined period of time. As depicted in Fig. 1b, by closing the NOP, it is also possible to connect a single large load using the spare capacity from both radial feeders (where each feeder has a maximum thermal capacity for 6 MVA of load). Network automation is important for ensuring correct and timely restoration of customers after faults, and for managing the available capacity.

A field trial of C₂C operation is presently underway, involving 180 ring circuits throughout the Electricity North West network, as shown in Fig. 2. These circuits have been selected due to their relatively low historical rates of fault occurrence, and to ensure that excessive fault levels are not introduced by closing NOPs; these practical conditions would also be applicable if the C₂C method is offered beyond the trial period. From the 180 trial circuits, 36 circuits have been selected for detailed monitoring and analysis.

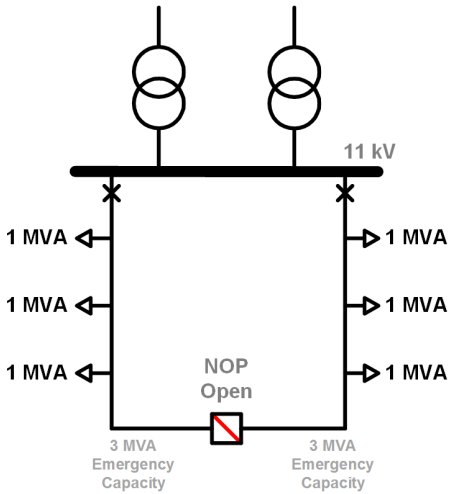
III. ELECTRICAL SYSTEM MODELLING

A. Circuit Data

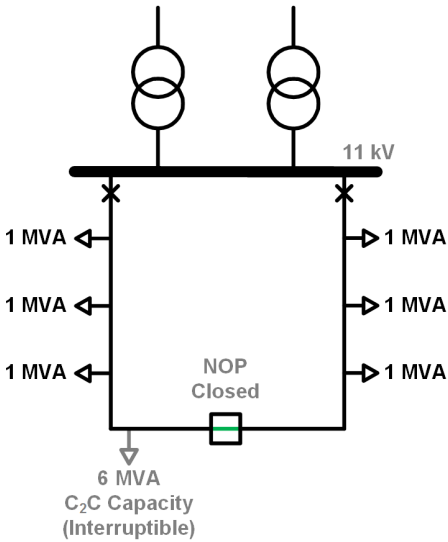
Data have been combined from a variety of sources, including: detailed distribution network data (including the full electrical topology) in a legacy format; cable and overhead line capacity ratings and impedance values; and historical loading

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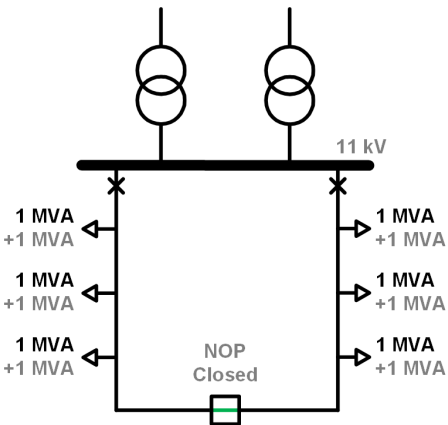
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(a) Conventional radial operation, with no usable spare capacity (emergency capacity not presently offered to customers)



(b) C₂C operation, with additional capacity for interruptible loads (large, single load)



(c) C₂C operation, with additional capacity for interruptible loads (distributed load growth)

Fig. 1. Capacity increase due to C₂C network operation

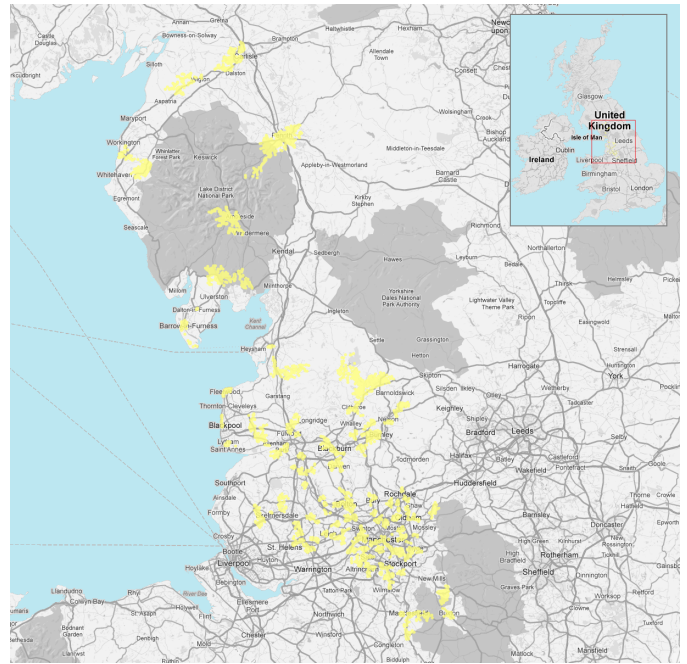


Fig. 2. Map of C₂C trial locations highlighted in yellow, from [5] (Map data ©2013 GeoBasis-DE/BKG (©2009), Google)

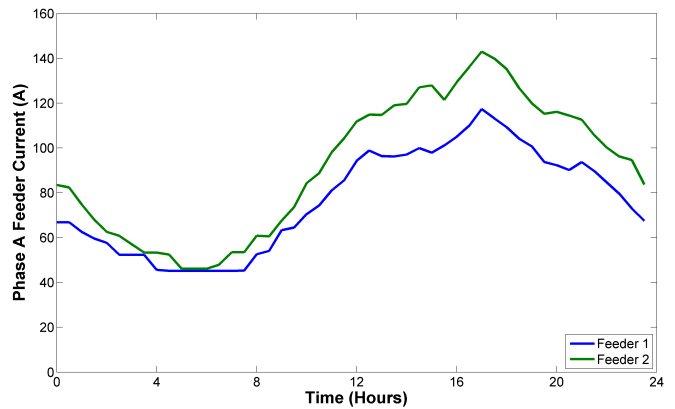


Fig. 3. Example half-hourly feeder current, 1st January 2012

data for all of the year 2012. Fig. 3 and Fig. 4 illustrate typical load current values for two radial feeders which form a ring circuit.

IPSA [6] has been used as a platform for integrating the data sources, as well as providing load flow functionality for analysing the performance of the selected ring circuits. Fig. 5 summarises the process of integrating the data sources and generating results. This process is fully automated for all 36 ring circuits.

The circuit loading data (as shown in Fig. 4) are processed to interpolate missing data values, although less than 0.5% of load current values are missing due to issues with the SCADA system or otherwise. The mean and peak annual loadings for each feeder are calculated and extracted.

The electrical network data is imported into IPSA. Although IPSA has legacy data import functionality, this process has been significantly extended to cater for the requirements of

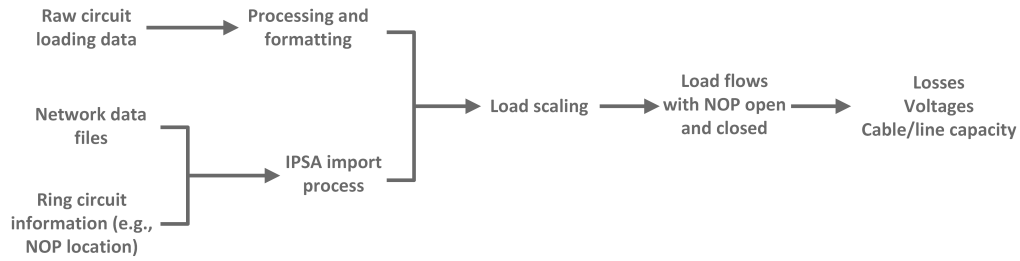


Fig. 5. IPSA import process

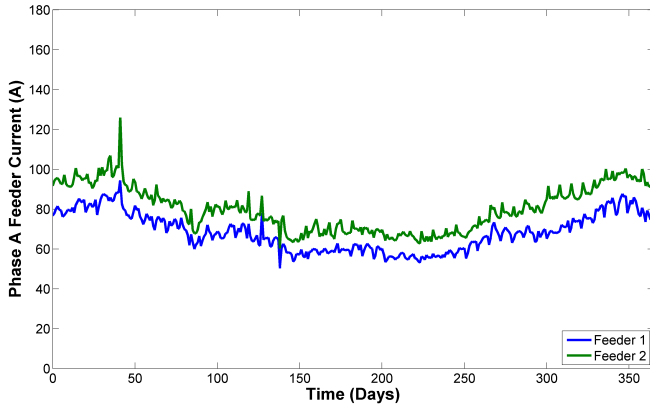


Fig. 4. Example daily mean feeder current, for 2012

this investigation. A geographically-accurate IPSA model of each ring circuit is generated, as illustrated in Fig. 6. Each substation, represented by blue dots in Fig. 6, has a load connected. For simplicity, it is assumed that no distributed generation is connected to the system.

A script is executed within the IPSA scripting environment to:

- 1) Validate the electrical connectivity of the models.
- 2) Remove necessary elements from each model.
- 3) Connect a generator to the primary busbar to represent the grid infeed.
- 4) Determine the load scaling factor which matches the historical loading data for each feeder (based on either the annual mean or annual peak loading data).
- 5) Perform load flows, in both radial and interconnected configurations, and generate the results.

B. Typical Circuit Results

Fig. 7a and Fig. 7b illustrate typical load flow results using IPSA, with the system operating in radial and interconnected configurations, respectively.

IV. RESULTS

A. Losses

Fig. 8 summarises the effect of C₂C operation on electrical (I^2R) losses, by extrapolating the reduction in total annual losses resulting from interconnected ring circuit operation (relative to radial operation). The majority of ring circuits exhibit

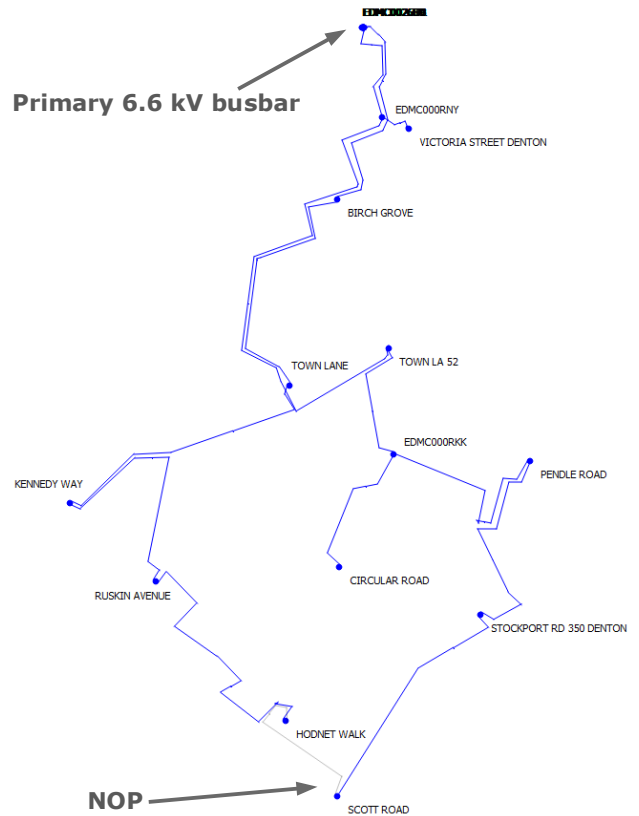


Fig. 6. Example of IPSA model of a ring circuit (blue dots represent substations)

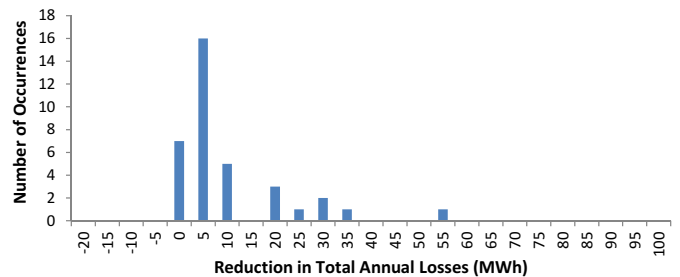
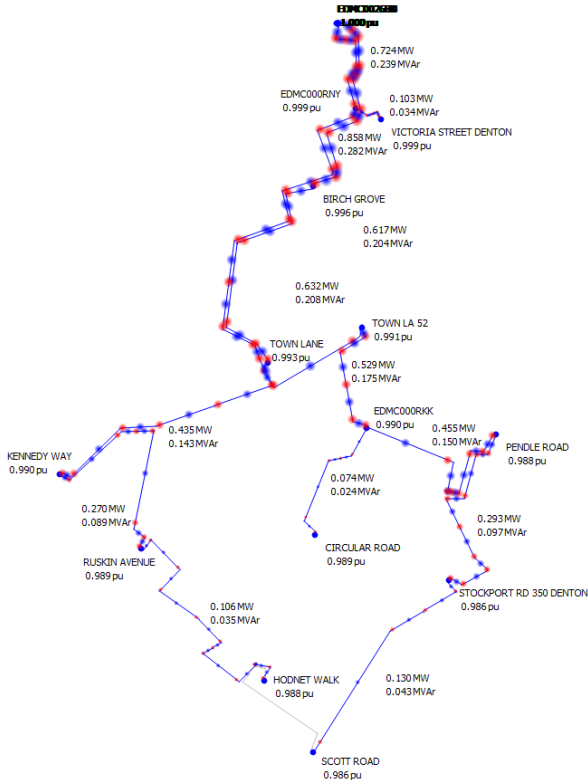
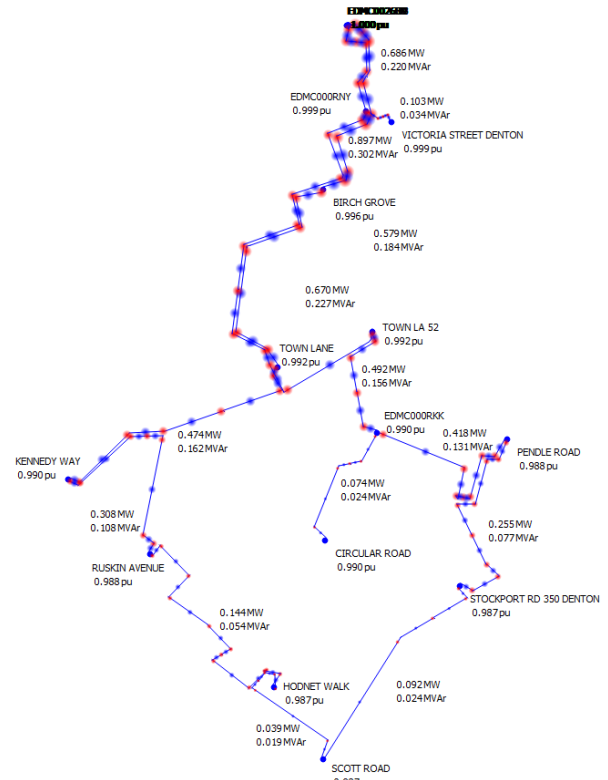


Fig. 8. Histogram of reduction in annual losses



(a) Load flow—radial configuration, mean loading



(b) Load flow—interconnected configuration, mean loading

Fig. 7. Example load flow results

an annual reduction in losses of approximately 5 MWh with the C₂C configuration, assuming mean loadings. This equates to a modest reduction in the mean distribution losses, for the 6.6/11 kV ring circuits under study; the mean total losses are reduced from 0.57% (radial) to 0.53% (interconnected).

B. Voltage

Fig. 9 illustrates the effect of interconnected operation on the minimum voltage experienced at any point in the ring circuit, at peak loading. These data include all spurs which branch off from the main circuit, which may experience lower voltages than the voltage at the NOP. In most cases, the minimum voltage shows an improvement due to interconnected operation, even at peak loading.

C. Capacity

The potential capacity available by adopting C₂C operation has been determined from the maximum possible additional interruptible load which can be connected, assuming that the load growth is distributed evenly throughout each ring circuit. Initially, each circuit is loaded to the conventional (i.e., according to ER P2/6) maximum capacity for non-interruptible loads. In each case, the load is increased until either:

- 1) A cable or line thermal headroom (i.e., the remaining thermal capacity) constraint is reached, or
- 2) A steady-state bus voltage constraint is reached (voltage less than 95% nominal voltage).

TABLE I
COMPARISON OF CIRCUIT CONSTRAINT TYPES

	Radial operation	Interconnected operation
Voltage constraints	22%	17%
Thermal constraints	78%	83%

The results are provided in Fig. 10. Approximately 80% of circuits are limited by a thermal constraint rather than a voltage constraint, as given in Table I. For interconnected operation, a mean increase in loading of 74% is possible, compared with 66% for radial operation; this can be attributed to the reduced occurrence of voltage constraints as shown in Table I. For circuit 16 in Fig. 10, which is a rural network with a significant presence of relatively long overhead lines, the system presently operates close to the voltage limit and there is no prospect for directly adding any interruptible load (without also implementing other measures to support the network voltage).

V. CONCLUSIONS

The results arising from the analyses of several circuits show that there generally are benefits to distribution losses and voltage support from increased interconnection, but these gains are often marginal. By allowing the connection of interruptible loads, the available capacity for distributed load is significantly

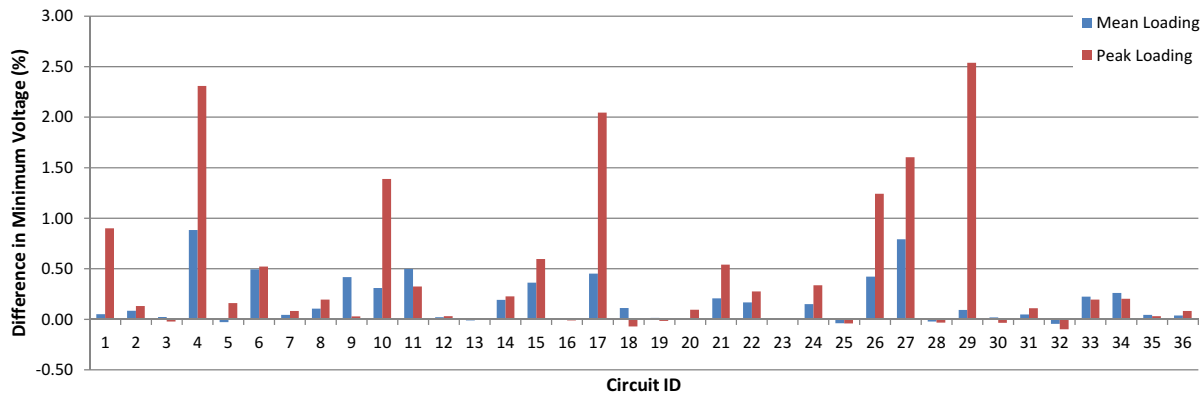


Fig. 9. Summary of difference in minimum voltage for C₂C operation

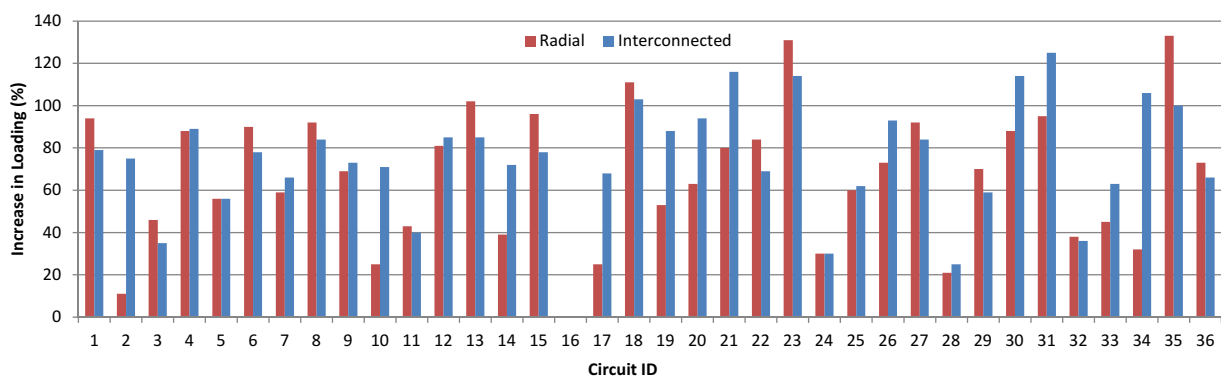


Fig. 10. Possible increase in circuit capacity resulting from C₂C operation

increased, by approximately 74%. Interconnected operation yields a further improvement in the available capacity, as well as potentially permitting the use of spare capacity from both radial feeders.

Further work will analyse the impact of interconnection when connecting distributed generation and the feasibility of connecting single, large loads without requiring conventional network reinforcement. The effects of C₂C operation on power quality will be evaluated, using data captured from power quality monitoring equipment during the trial.

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