

# Opportunities for Interconnection of Adjacent Distribution Feeders in GB Networks

James Dixon, Keith Bell, Ian Elders  
Dept. of Electronic and Electrical Engineering  
University of Strathclyde, Glasgow, United Kingdom  
{james.dixon, keith.bell, i.elders}@strath.ac.uk

**Abstract**— This paper presents an investigation into the potential benefits of interconnecting adjacent 33 kV demand groups in the GB distribution network by presentation of two case studies. Results presented are, firstly, a comparison of load profiles of adjacent groups and, secondly, following application of a series of credible future scenarios, the potential reduction in loss of load and generation curtailment achievable from interconnection and the proportion of time for which interconnection would be utilised.

It was found that there is significant dissimilarity between load profiles of the adjacent groups analysed and interconnection could be valuable for the future distribution system. The value of interconnection could be increased with the use of storage, though more analysis is needed to quantify the economic viability of this.

**Index Terms** – interconnection, distribution networks

## I. INTRODUCTION

Traditionally, distribution networks are operated radially rather than interconnected due to greater simplicity and lower cost in protection requirements [1]. To maintain reliability, Normally Open Points (NOPs) between groups can be closed in the event of an outage to re-supply customers without power. As increasing value is placed on the flexibility of generators and loads to suit the move to increasing penetration of intermittent Distributed Generation (DG) [2], there may be significant value in interconnecting adjacent groups: allowing generators and customers to share excess renewable generation and peak demand, storage operators and Demand Side Response (DSR) aggregators to access a greater market for their services and Distribution Network Operators (DNOs) to defer expensive traditional reinforcement.

### A. Interconnection in Distribution Networks

There are three methods of interconnecting demand groups, herein referred to as ‘hard’, ‘dynamic’ and ‘soft’. The methods presented in this paper are applicable to any of the three forms discussed; however, the operation and attainable benefits will depend on which method of interconnection is used.

#### 1) ‘Hard’ interconnection

‘Hard’ interconnection refers to the permanent closure of NOPs and running the network as a mesh. An example of this

is the MANWEB network operated by SP Energy Networks. Due to its interconnected operation, MANWEB customers have the least interruptions of any DNO area in GB but also the highest use of system tariffs due to the cost of enhanced protection [3]. This high cost has meant that radial designs have prevailed over interconnected for the majority of cases.

Hard interconnection has been re-visited in recent years due to its perceived flexibility and ability to accommodate increased intermittent DG and low-carbon loads such as electric vehicles and heat pumps. The techniques have been trialled in real networks in the Capacity to Customers (C<sub>2</sub>C) [4] Low Carbon Network Fund (LCNF) project. Technical analysis of C<sub>2</sub>C interconnection [5] concludes that the benefits reaped, if any, depend largely on the network characteristics: while hard interconnection can increase capacity release for networks with asymmetric loading between adjacent feeders, it can prove detrimental to networks which have asymmetric impedances between feeders relative to their thermal ratings.

The introduction of hard interconnection into radial networks remains a fair distance from a Business as Usual technology [6] due to a lack of evidence that the benefits would outweigh the significant increase in cost.

#### 2) ‘Dynamic’ interconnection

‘Dynamic’ interconnection refers to closing and opening switches in a network to shift load and generation around a system. The radial constraint is maintained, which makes protection requirements simpler [1], but the end goal of allowing adjacent feeders to share generation and demand as in ‘hard’ interconnection is attained. This ‘best of both worlds’ appeal has generated much research interest around dynamic interconnection: [1], [8] and [9] present alternative methods of optimising the real-time reconfiguration of distribution networks with high DG penetration. Although it escapes the protection requirements of hard interconnection, dynamic interconnection requires a reliable IT/communications network to enable real-time monitoring and remote controlled switching.

This method has been trialled in real networks as part of the Flexible Networks LCNF project [9] which allowed remote control of switches to balance load between adjacent 11 kV feeders. The project reports a 6-11% potential capacity headroom increase from the dynamic switching actions.

### 3) 'Soft' interconnection

'Soft' interconnection refers to the installation of power flow control devices in place of existing NOPs. The main technologies that might be used include phase shifting transformers and back-to-back power electronic AC/DC converters, examples of a range of technologies known as 'Flexible AC Transmission Systems' (FACTS) albeit applied at distribution voltages [10]–[15]. They allow the power flows on adjacent, interconnected circuits to be controlled in order to maximise the use of available thermal headroom on those circuits in meeting peak demand or minimising the curtailment of generation within the connected groups. Furthermore, SOPs can control local voltage, limit fault current and allow transfer between groups whilst respecting voltage and thermal limits of any interconnecting branches [12].

### B. Objectives

The objectives of the work reported here are, firstly, to evaluate the similarity of loading profiles of representative GB distribution networks to investigate the potential for power flow between them (Section II). For confidentiality reasons, the networks are reported as A, B, C and D. Then, for a series of credible future scenarios relating to increasing generation and demand (Section III), to investigate the potential of interconnection to relieve import and export constraints of the same example groups and quantify the expected utilisation of interconnection in such scenarios.

## II. PRESENT NETWORK ANALYSIS

### A. Group A and Group B, 33 kV

Group A serves five primary (33/11 kV) substations with a 58 MW combined peak load from a Grid Supply Point (GSP) of firm capacity 120 MW. It is separated by four NOPs from Group B which serves four primary substations with a peak load of 47 MW and a firm capacity of 120 MVA. Group B accommodates a 12 MW wind farm.

Fig. 1 shows a comparison between the load curves of the two groups for a winter week (18-25 January 2016).

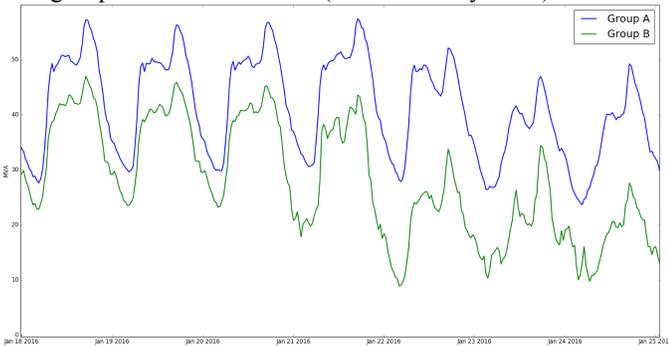


Fig. 1. Groups A and B load curves for typical winter week in 2016

Fig. 1 shows that there is some unbalance between the groups: The Group A loading is consistently higher and the presence of the wind farm on Group B renders its load curve

less regular: for times when wind output is high, there could be significant headroom available on Group B.

### B. Group C and Group D, 33 kV

Group C serves three primary (33/11 kV) substations with a group peak load of 28 MW and a firm capacity of 90 MVA. It is separated by two NOPs from Group D which serves two primary substations also with a group peak load of 28 MW and a firm capacity of 60 MVA. There is no metred generation currently installed within these groups. Fig. 2 shows a comparison between the load curves of the two groups for a winter week (16-23 December 2016).

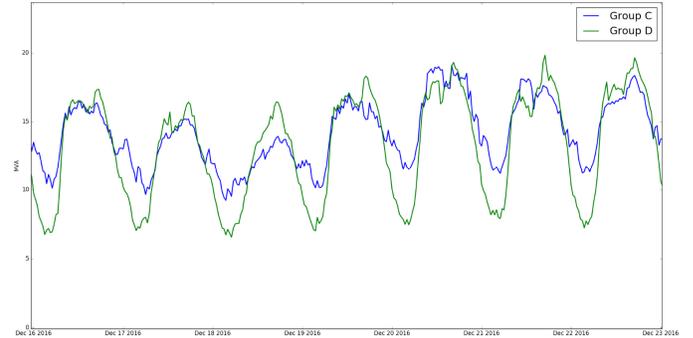


Fig. 2. Groups C and D load curves over a typical winter week in 2016

Fig. 2 shows an example of demand diversity between groups, where one group (C) is industrially-dominated (experiencing a peak in the middle of the day) and the other (D) is primarily residential (experiencing a lower dip at night and a higher peak in the evening).

### C. Results

Interconnection is potentially useful when a constraint experienced in one group (at a peak) can be relieved by transferring power to/from another. To numerically analyse the potential for power transfer between the two load profiles, these steps were followed:

1. Split a yearly profile into 365 daily profiles
2. For each day:
  - a. Identify the daily peak net load (import or export) on either group
  - b. Find the difference between that peak and the corresponding value on the other group at the same instant in time
  - c. Report the mean, minimum, maximum and standard deviation of (b) throughout the year reported in absolute terms (MVA) and as a percentage of the daily peak for each group pair

Table 1. Analysis of absolute difference between loading of adjacent feeders

	Mean	Min.	Max.	Std.
<b>Groups A &amp; B</b>	13.73 MVA (31.49%)	3.97 MVA (10.62%)	29.33 MVA (66.72%)	5.36 MVA (11.44%)
<b>Groups C &amp; D</b>	5.02 MVA (25.81%)	0.87 MVA (4.63%)	11.16 MVA (44.9%)	1.58 MVA (6.71%)

Table 1 shows that both pairs of feeders exhibit significant dissimilarity throughout the year. The dissimilarity is generally higher for Groups A & B, which is thought to be due to the difference in peak demands of the groups and the presence of the wind farm. Although the difference between the loading for Groups C & D is generally less, the shapes of the daily load curves (Fig. 2) do differ, which may prove an interconnector valuable to relieve constraints.

As the peak loading of the feeders is significantly lower than the firm capacity of the grid, the results do not translate to value in interconnection. On this basis, analysis of credible future scenarios is carried out to investigate potential value in an evolving energy system with new, peaky loads and significant DG installation.

### III. FUTURE NETWORK ANALYSIS

#### A. Reduced Network Model

The networks were modelled as simple groups with generation, demand and a transformer capacity for export/import to/from the grid. The interconnector can allow power flow between the groups in either direction (Fig. 3).

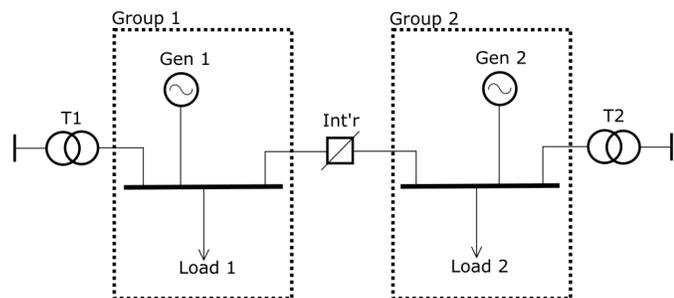


Fig. 3. Reduced network model for study

For a given generation output and load with fixed transformer capacity, a group will be in one of four states:

1. *Export Constrained* – generation surplus is higher than the available export capacity on the transformer. The group will look to export to the other group subject to the interconnector capacity and the spare export capacity on the other group. Any generation that cannot be exported is curtailed.

2. *Import Constrained* – generation deficit is higher than the available import capacity on the transformer. The group will look to import subject to the interconnector capacity and the spare import capacity plus any surplus generation on the other group. Any demand that cannot be satisfied by importing from the interconnector will be loss of load.

3. *OK* – Either surplus is less than the available export capacity or deficit is less than the available import capacity. The group does not need to use the interconnector, but may import or export up to the capacity of the interconnector and its own capacity to relieve constraints on the other group.

#### B. Credible Future Scenarios

##### 1) Demand Growth

It is projected that the demand increase on the electricity system in GB to 2050 will be mostly due to the electrification of heat and transport and that the increase in peak demand will be disproportionately higher than the increase in energy usage [16]. One of the most prominent studies of the evolution of demand in a GB distribution network is the Low Carbon London LCNF project, which claims that a three-fold increase in peak demand could be expected to 2050 if uptake of electrified heat and transport is high [17]. This multiplication factor of 3 is hence applied as the ‘high demand’ outcome.

##### 2) Generation Growth

It is expected that there will continue to be significant growth in the number of intermittent renewable DG connections in GB distribution networks [18]. For this study, two types of intermittent generation are considered: wind and solar PV. In order to represent a credible time series of wind farm generation to superimpose on a time series of demand in order to find the net power transfer, the output of the Group B wind farm was used and scaled for any desired peak output. For the solar PV dataset, Renewables.ninja [19]–[21] was used to generate hourly power output data which could be linearly interpolated to half-hourly and scaled for any peak output (parameters: 35° tilt, 10% system losses, no tracking, 180° azimuth; location: 55.7° N, 4.2° W).

To investigate the likely uptake of DG, the SPEN DG Heat Map [22] was used to query the total DG in various generation-led networks in Scotland which are suffering constraints due to generation level and hence find typical ratios between firm network capacity and how much generation capacity could be accommodated. A sample of five networks is shown in Table 2.

Table 2. Sample of generation-dominated groups

	Coylton	Chapel-cross	Galashiels	Eccles	Berwick
<b>Firm capacity <math>F</math> (MVA)</b>	60	90	45	60	60
<b>Generation <math>G</math> (MW)</b>	164.0	194.0	100.3	85.6	121.9
<b><math>G/F</math></b>	2.7	2.2	2.2	1.4	2.0

The average of the ratio  $G/F = 2.1$ . It was therefore decided that a reasonable ‘high generation’ scenario would be for the peak generation to be twice the group firm capacity. To investigate the effect of diversity in generation, the future scenarios make use of both wind and solar generating profiles.

##### 3) Future Scenarios

The future scenarios as reasoned in the previous two sections are summarised in Table 3. Legends in the charts presented in Figs 4-7 refer to these scenarios by the number in Table 3. Note that ‘low’ refers to no change from the current value.

Table 3. Future scenarios for generation and demand increase for use in study

Scenario	Group 1	Group 2
I	High demand, low generation	Low demand, low generation
II	High demand, low generation	High demand, low generation
III	High demand, high generation (wind)	High demand, high generation (wind)
IV	High demand, high generation (wind)	High demand, high generation (solar)

C. Results

After the future scenarios are applied, the peak loading on the groups exceeds their firm capacity and there becomes loss of load (demand that cannot be met) and curtailment of generation that cannot be exported. By installing a controllable interconnector (such as a SOP), the loss of load and generation curtailment can be reduced. This section presents the extent to which they can be reduced for each future scenario in Table 3.

1) Loss of Load Reduction

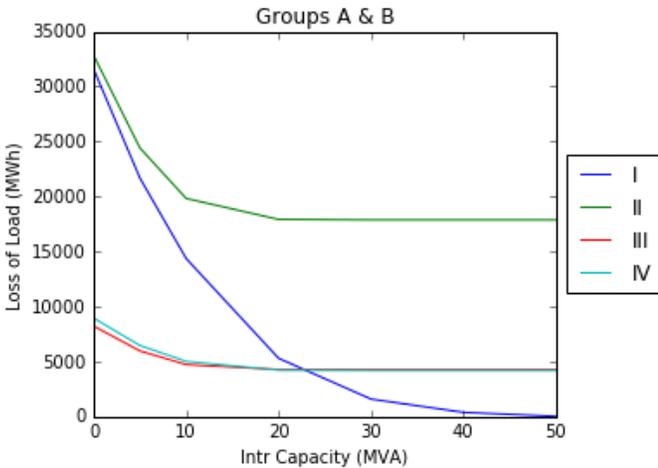


Fig. 4. Loss of load reduction from interconnection in Groups A & B

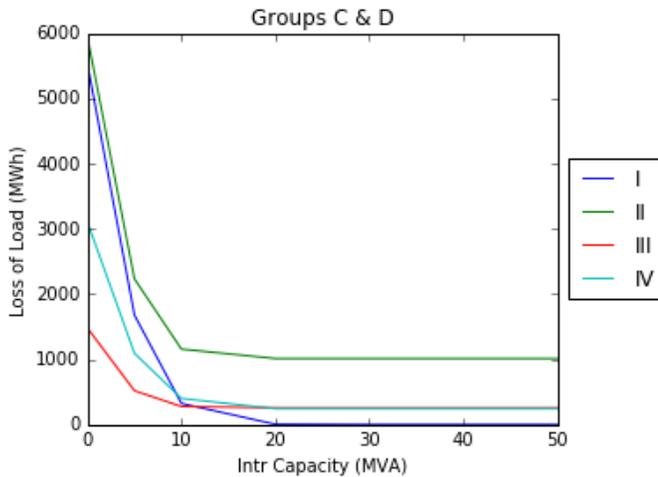


Fig. 5. Loss of load reduction from interconnection in Groups C & D

Figs 4 & 5 show a significant reduction in loss of load from interconnection for all future scenarios. In both group pairs, an interconnector of 50 MVA capacity can eliminate loss of load for Scenario I. This is because only one group has increased demand, so the peaks greater than the firm capacity can be met by the other group, which has plentiful headroom. In practice, interconnection might not be a cost-effective solution to a large demand increase on one group; it should be compared with moving the NOP along the network to better balance the loading of the groups.

In both networks, Scenario II shows a significant reduction in loss of load but shows a diminishing return on loss of load reduction with interconnector capacity and at some point there is ‘saturation’ of the benefit: at this point no more power can be transferred as the peaks of the groups have now become concurrent and they have both reached the limits of import capacity through their respective transformers. The saturation of the Groups C & D interconnector occurs at a lower capacity than for Groups A & B as the absolute difference between the load profiles (Table 1) is lower. The proportional reduction in loss of load is higher for Groups C & D because even after the application of a 3x demand increase, the loading of the Group C group remained below the firm capacity most of the time, with the exception of a few winter peaks – hence there was normally adequate headroom to serve the Group D load through an interconnector.

For Scenarios III and IV, the loss of load for zero interconnection is lower because the presence of generation is able to serve more of the load. The loss of load is lower for Scenario III, which reflects the fact that wind output is better correlated with demand in GB (which experiences a winter peak load) than solar. The same saturation effect occurs, but the interconnector is able to reduce loss of load to a lower value than for Scenario II as it can transfer surplus generation from one group to meet demand on the other.

2) Generation Curtailment Reduction

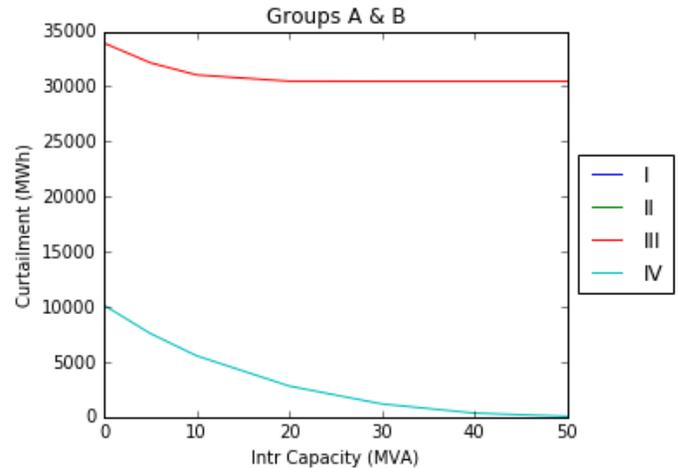


Fig. 6. Curtailment reduction from interconnection in Groups A & B

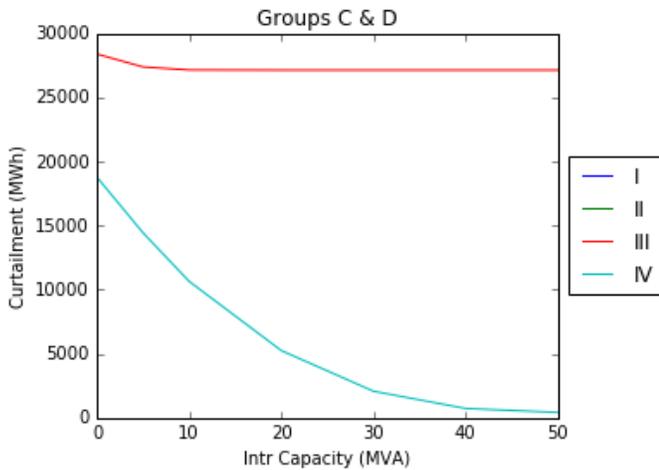


Fig. 7. Curtailment reduction from interconnection in Groups C & D

For the curtailment reduction study, both pairs of groups show similar results. Scenarios III and IV both see significant generation (twice the group firm capacity) installed, but Scenario III sees homogeneous generation as both groups are wind-dominated whereas Scenario IV sees heterogeneous generation as one group is wind-dominated whereas the other is solar-dominated.

Curtailment is initially higher (at zero interconnection) for Scenario III than IV. This is because although the peak solar and wind output are set to be equal, the total wind energy generated over the year is much greater (by a factor 2.1) than the total solar energy over the year in the profiles used.

Both Figs 6 and 7 show that there is much more potential for interconnection between groups with heterogeneous generation, as the diversity of renewable generation can be taken advantage of. Scenario III and IV represent two extremes of DG uptake: although the outcome will be somewhere between the two, it is more likely to be more similar to Scenario III than IV as the renewable resource of two adjacent groups is likely to be similar.

### 3) Interconnector Utilisation

As the simulation is run over the course of a year, the combination of states of the groups in the reduced network model (Fig. 3) dictates whether an interconnector would be used or not. From the previous section, there is most value to interconnection in situations in which adjacent groups experience different constraints at a particular moment in time, e.g. one is import constrained when the other is export constrained. When both groups experience the same constraint (either both import constrained or both export constrained), storage might be of value as an alternative to reinforcing the connections back to the main grid.

Figs 8 and 9 show the utilisation of interconnection for both group pairs for all future scenarios considered.

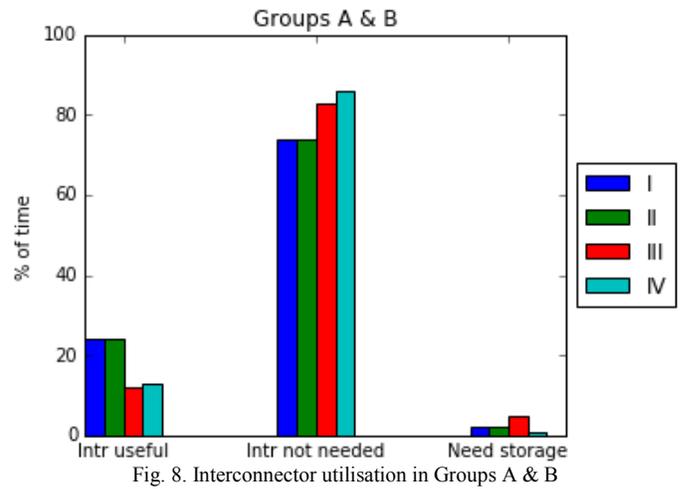


Fig. 8. Interconnector utilisation in Groups A & B

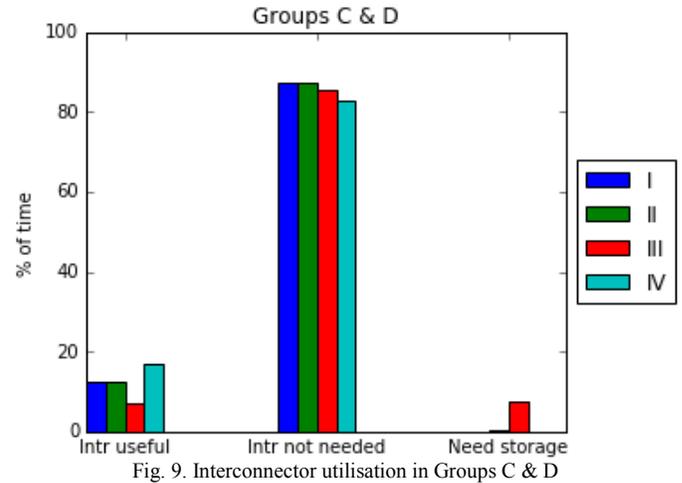


Fig. 9. Interconnector utilisation in Groups C & D

In both pairs of groups, the interconnector is not needed for the majority of the time. This could be expected due to the peaky nature of electricity consumption – even if it were operating for an hour every day throughout the year, the utilisation would be less than 5%. At a maximum, the results for Groups A & B show that there is potential for an interconnector to be used 24% of the time in a high demand/low generation scenario due to the dissimilarity between load profiles. If storage were installed with the interconnector and providing it was sized sufficiently, it could bring the loss of load and curtailment down to zero for all future scenarios. However, the results in Figs 8 & 9 show that the proportion of time for which the interconnector would need storage is small: the largest (Scenario III, Groups C & D) was found to be 7.4%. These results cast doubt on the business viability of this as a solution: in order to make the inclusion of storage economically viable, other revenue streams (e.g. grid services such as fast frequency response) would have to be identified [23].

#### IV. CONCLUSION AND FUTURE WORK

The analysis in Section II shows that there are differences in the occurrence of peaks on adjacent demand groups, which could be exploited by an interconnector to help balance the distribution system. However, in the networks examined the peak loading is well below the firm capacity of the group and no value in interconnection was identified for the trialled networks in their present condition.

As the distribution system evolves to accommodate increasing DG and demand, the analysis in Section III shows firstly that interconnection can relieve import and export constraints and secondly that the potential value of interconnection is sensitive to the level of generation and demand uptake and the diversity in generation technologies (e.g. wind and solar) in the future distribution system.

It may well be that significant growth in demand or DG would require at least some conventional network reinforcement. Nonetheless, interconnection between groups promises to maximise the utilisation of given network capacity in adjacent groups. The analysis presented shows the diminishing return of interconnector value with increasing capacity and the point at which an interconnector ‘saturates’; this kind of analysis could be used to size the interconnector correctly to maximise its efficiency – whether that means the range of operation of a dynamic reconfiguration scheme or the capacity of a SOP. The point of ‘saturation’ where benefits can no longer be reaped is represented by the proportion of the time that the groups are in the same state (i.e. both import constrained or both export constrained) and the interconnector requires storage to provide value. It is shown that this is a small proportion of the time for any case and this result casts doubts over the economic viability of this as a solution. Research into the possible business case of the combination of distribution-level storage and interconnection is identified as a piece of future work to be carried out.

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