Keywords: Distribution Network, Planning, Demand Side Response, Capacity Credit.

Abstract

The present UK distribution network planning standard, Engineering Recommendation P.2/6 (P2/6), defines the acceptable durations of supply outages following first and second circuit outage conditions as function of group demand. In addition, P2/6 specifies a capacity value for distributed generation (DG) to be used in future circuit capacity planning. The approach does not consider other elements of the distribution network. This paper analyses the reliability performance of distribution system when DSR is used to defer network upgrades driven by load growth. The analysis uses actual DSR performance data from trials that were executed as part of the Low Carbon London project. The DSR contribution to security of supply is assessed using a probabilistic risk modelling framework to further inform a number of topics (i) reliability contribution of DSR technologies in a network context, (ii) strengths and weaknesses of P2/6 in estimating contribution to security of supply, (iii) benefits of contractual redundancy, (iv) impact of DSR coincidence in delivery (common mode failures) on contribution to security, and (v) impact of DSR scale and magnitude on contribution to security of supply.

1 Introduction

The present UK distribution network planning standard, Engineering Recommendation P.2/6 (P2/6) [4], defines the acceptable durations of supply outages following first and second circuit outage conditions as function of group demand. In addition, P2/6 specifies a capacity value for distributed generation (DG) to be used in future circuit capacity planning. The capacity values for the contribution of DG are derived using a probabilistic calculation [1]. The P2/6 approach applies reliability modelling of individual non-network technologies that does not consider other elements of the distribution network. Because the reliability delivered to end consumers is ultimately driven by the combined reliability characteristics of the network and DSR elements, the P2/6 approach offers limited insight into the actual reliability implications associated with the use of DSR in particular scenarios [2].

This paper analyses the reliability performance of distribution networks when DSR is used to defer network upgrades driven by load growth. The analysis uses actual DSR performance data from trials that were executed as part of the Low Carbon London project [5]. The DSR contribution to security of supply is assessed using a probabilistic risk modelling framework to further inform a number of topics (i) reliability contribution of DSR technologies in a network context, (ii) strengths and weaknesses of P2/6 in estimating contribution to security of supply, (iii) benefits of contractual redundancy, (iv) impact of DSR coincidence in delivery (common mode failures) on contribution to security, and (v) impact of DSR scale and magnitude on contribution to security of supply.

2 Summary of trials

The response and number of dispatches of demand-led DSR technologies demonstrated in Low Carbon London are shown in Table 1. There were a total of 17 demand-led DSR facilities with a total demand reduction capability of 3,330kW.

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of installations</th>
<th>Total requested response (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHP</td>
<td>5</td>
<td>6695</td>
</tr>
<tr>
<td>Diesel</td>
<td>3</td>
<td>6000</td>
</tr>
<tr>
<td>Demand-led DSR</td>
<td>17</td>
<td>3330</td>
</tr>
</tbody>
</table>

Table 1: Total DSR requested responses. Source: [6]

Figure 1 show the average response probabilities (in % of contracted response) for demand-led DSR facility as recorded from Low Carbon London industrial and commercial DSR trials [6]. For example, probability of average demand-led DSR facility to deliver more than 97.5% of contracted capacity is about 52% and to deliver less than 2.5% is about 20%. The remaining 28% is for states in between.

Figure 2 shows the piecewise approximation of the average load duration curve of the eight primary sites [6].

3 Description of approach

An analysis of the reliability performance of distribution networks can be used to define a capacity contribution of DSR by deriving ‘risk-equivalent’ networks. The equivalents are defined with respect to the Expected Energy Not Supplied
(EENS) metric. The equivalents can be defined in a number of ways. In addition to the method specified in P2/6, we consider alternative capacity contribution definitions that are inspired by the following metrics that are commonly used for network adequacy studies:

- Effective Load Carrying Capability (ELCC) is the amount by which the load may be increased in the presence of DSR facilities while the original risk is maintained,
- Equivalent Firm Capacity (EFC) is the amount of capacity of an always available source that can replace DSR facilities while the supply risk is maintained, and
- Equivalent Network Capacity (ENC) is the increase in network capacity based on an equivalent circuit with the reliability performance of the real network, which can replace DSR facilities while the supply risk is maintained.

3.1 Effective Load Carrying Capability

The ELCC directly specifies the ability to increase the maximum group demand in the presence of DSR and it is the amount by which the load may be increased in the presence of DSR facilities while the original risk is maintained. An illustration of the effective load carrying capability approach is shown in Figure 3.

Figure 3: Illustration of the ELCC approach

In this approach the EENS risk measure is calculated for the system including network circuits but excluding DSR facilities, see Figure 3 on the right. The maximum group demand that satisfies the P2/6 criteria (N-1) is used. Then the increase of Group Demand (ELCC = ∆D_max) which will produce the same value of the risk indicator when DSR facilities are included, while satisfying P2/6 conditions, is calculated, see Figure 3 on the left. The contribution to security of supply is then equal to the Group Demand increase.

3.2 Equivalent firm and network capacities

Equivalent Firm Capacity (EFC) is the capacity of the ideal source (Y) and Equivalent Network Capacity (ENC) is obtained by increasing circuit capacity (∆X), which can replace DSR facilities without changing the supply risk, as illustrated in Figure 4.

Figure 4: Illustration of EFC and ENC approaches

Note that whereas the ELCC is directly applicable to demand growth scenarios, EFC and ENC are generation-side metrics that must be transformed to increases in maximum group demand (detailed below) to be compared on an equal footing. In the following, the reliability performance of DSR as calculated by the P2/6 alternative metrics (ELCC, EFC and ENC) is compared against that of P2/6 to determine the equivalent network reinforcement. Risk implications of the P2/6 methodology and its alternatives are discussed.
In the EFC approach $\Delta X=0$, while in ENS $x=0$. Then the increase of Group Demand which will produce the same value of the risk indicator, while satisfying P2/6 conditions, is calculated. The contribution to security of supply is then equal to the Group Demand increase.

4 Illustration of reliability performance as delivered by DSR compared with network reinforcement

Each of the analyzed methods for determining the capacity credit of DSR facilities are compared with the network needed to ensure compliance to the security standard. For illustration, two transformer circuits are considered with each circuit rating of 15 MVA. Different reliability of circuits is considered assuming failure rate of 2% and 20% occurrences per year with mean time to repair (MTTR) of 24 and 240 hours. Three demand-led DSR facilities, see Figure 1, each capable of reducing 1 MW of demand are considered.

<table>
<thead>
<tr>
<th>MTTR (h)</th>
<th>Failure rate (%)</th>
<th>Method</th>
<th>Contribution</th>
<th>$\Delta$D (MW)</th>
<th>EENS (kWh) Using DSR</th>
<th>Conventional up-rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>2%</td>
<td>P2/6</td>
<td>60.0%</td>
<td>1.80</td>
<td>5.40</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ELCC</td>
<td>11.9%</td>
<td>0.36</td>
<td>0.32</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EFC</td>
<td>11.7%</td>
<td>0.35</td>
<td>0.32</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ENC</td>
<td>12.6%</td>
<td>0.38</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>20%</td>
<td>P2/6</td>
<td>60.0%</td>
<td>1.80</td>
<td>81.43</td>
<td>35.54</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ELCC</td>
<td>26.2%</td>
<td>0.79</td>
<td>31.73</td>
<td>33.39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EFC</td>
<td>25.3%</td>
<td>0.76</td>
<td>31.35</td>
<td>33.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ENC</td>
<td>30.4%</td>
<td>0.91</td>
<td>33.66</td>
<td>33.66</td>
</tr>
<tr>
<td>240</td>
<td>2%</td>
<td>P2/6</td>
<td>60.0%</td>
<td>1.80</td>
<td>81.43</td>
<td>35.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ELCC</td>
<td>26.2%</td>
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</tr>
<tr>
<td></td>
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<td>ENC</td>
<td>30.4%</td>
<td>0.91</td>
<td>33.66</td>
<td>33.66</td>
</tr>
<tr>
<td>20%</td>
<td>P2/6</td>
<td>60.0%</td>
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<td>3.526</td>
<td>3.519</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>ELCC</td>
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<td>1.41</td>
<td>3.142</td>
<td>3.437</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EFC</td>
<td>43.8%</td>
<td>1.31</td>
<td>3.076</td>
<td>3.417</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ENC</td>
<td>59.8%</td>
<td>1.79</td>
<td>3.518</td>
<td>3.518</td>
</tr>
</tbody>
</table>

Table 2: Results for an example with three DSR facilities

Results are shown in Table 2. The group demand increase achieved with the DSR facility is shown, as calculated by each of the methods. In each case, the group demand increase could have been equally achieved with a conventional replacement of both transformers with a rating equal to D+AD. Importantly the two columns under Expected Energy Not Served (EENS) quantify the energy at risk in the two cases, of using the DSR facility and using the conventional up-rating approach. The EENS is calculated as the sum of expectations of energy not supplied across all system states. The expectation of energy not supplied for one state is calculated by multiplying the area under the load duration curve and above the state capacity with state probability. This includes all potential combinations of intact system, N-1, N-2, etc. The LDC is obtained by using the average LDC shape shown in Figure 2, scaled to match the Group Demand.

As expected, in highly reliable networks (characterised by low circuit failure rates and short repair/restoration times) the ELCC, EFC and ENC methods allocate a much lower contribution to DSR if that same high reliability is to be maintained and hence would result in a lower increase of Group Demand when compared with P2/6. In practice however, this network reliability may already be well in excess of P2/6 requirements due to the other incentives, which are in place in the GB regulatory environment, in particular the Interruption Incentive Scheme. The ENC and P2/6 methods produce similar contributions in networks with low reliability (failure rate 20% and MTTR of 240 hours).

Furthermore, EENS when DSR is used to substitute for network reinforcement is very similar to the EENS in case of idealised conventional up-rating, when EFC, ENC and ELCC approaches are used. This is in stark contrast to P2/6, even though the contribution of DSRs is calculated in networks characterised with low reliability.

In case of P2/6 approach, a significant part of the expected energy not supplied is driven by the N-1 condition, while in the EFC, ENC and ELCC based methods the EENS is dominated by the N-2 condition.

Figure 5 shows the probability of DSR facilities meeting or exceeding the corresponding contribution. As expected, it can be seen that the probability of delivering a given contribution is higher for smaller contributions. In this context, the probability of delivery of a given contribution allocated by P2/6 is the lowest in this example. It should be noted that even though the contribution of DSRs is calculated in network setting the probability of delivery of a contribution depends only on DSRs states and probabilities.

Note that in case of ENC, driven by its very definition, the EENS, when DSR is used to substitute for network reinforcement, is exactly equal to the EENS in case of idealised conventional up-rating.
5 Contractual Redundancy

One way of increasing the probability of delivering the contribution made by DSR facilities is to introduce redundancy by choosing larger number of contracted facilities. The number of DSR facilities, each capable of demand reduction of 0.3 MW, is varied from 3 to 5. The individual state probabilities, shown in Figure 1, are used. Convolution is used to calculate the state probabilities for more than one facility. The average LDC shown in Figure 2 is used.

Figure 6 shows the contribution calculated by various approaches for three, four and five demand-led DSR facilities and a range of circuit reliability parameters. The P2/6 contribution factor increases from 60% to 62% if the number of demand-led DSR facilities increases from three to five. In other approaches the contribution is much smaller for more reliable circuits, but this increases more steeply as the number of demand-led DSR facilities increases. For further comparison, the probabilities of delivering the contributions Figure 6 are shown in Figure 7.

The probability of delivering a contribution by assuming a P2/6 contribution factor of 60% for three demand-led DSR facilities but contracting three, four or five facilities is shown in Figure 8.

It can be seen that the probability of set of DSR facilities delivering the P2/6 contribution increases from 62% to 82% for N-1 and to 92% for N-2 DSR redundancy. This is about a 50% increase in probability for contracting two more demand-led DSR facilities.

6 Coincidence in Delivery and Impact of Materiality

We proceed to investigate the effects of dependent DSR responses and the impact of the magnitude of the DSR response compared to the group demand. For illustration, two circuits are considered with each circuit having a rating of 15 MVA. Different reliabilities of circuits are considered, assuming failure rates of 2% and 10% per year with MTTR of 24 and 240 hours. Six demand-led DSR facilities and two scenarios in which DSR capacities are 0.3 and 2 MW respectively are considered. Convolution is used to calculate the state probabilities for the six facilities assuming different coincidences of delivery of 0%, 25% and 100%. The DSR response is assumed to be identical for all sites with a probability equal to the coincidence of delivery and independent otherwise.

The impact of demand-led DSR penetration and coincidence of delivery on contribution to security of supply by different approaches is shown in Figure 9. The X-axis represents (from bottom): coincidence in delivery, circuit MTTR and circuit failure rate. The Y-axis is contribution factor. It can be seen that the capacity contribution decreases as coincidence in delivery increases and also as the ratios of demand reduction capacity and circuits’ capacity increase. The EFC, ELCC and ENC approaches typically result in a lower contribution than the P2/6 approach. It should be noted that P2/6 contribution is independent of DSR penetration level, network capacity and reliability.
EFC approach, the EENS remains similar irrespective of coincidence in delivery. It slightly increases as the ratio of demand reduction capacity and circuit capacity increase by increasing the contribution to EENS from the N-1 condition. However, in the P2/6 approach the EENS increases as coincidence in delivery increases. The increase is due to the increase in EENS caused by the N-1 condition, while the EENS caused by the N-2 condition remains the same. The EENS significantly increases as the ratio of demand reduction capacity and circuit capacity increase due to the increasing contribution to EENS caused by the N-1 condition. For high ratios of demand-led DSR capacity and circuit capacity and high coincidence in delivery the majority of EENS is due to the N-1 condition.

**7 Conclusion**

The capacity contribution of DSR schemes is quantified following the philosophy of the present P2/6 used to calculate capacity contribution of DG. The P2/6 approach applies reliability modelling of individual non-network technologies without considering the actual distribution network. However, the reliability delivered to end consumers is ultimately driven by the reliability characteristic of both the actual network and DSR.

To analyse impact of the network reliability on the contribution of DSR, this paper compares the levels of capacity contribution that correspond to the different definitions established for the network adequacy studies:
ELCC, EFC and ENC. The ELCC, EFC and ENC approaches consider network reliability in quantifying the contribution to security of supply of DSR. The level of DSR contribution, measured by ELCC, EFC and ENC approaches have relatively similar performance, especially for ELCC and EFC approaches.

Although this analysis identified a number of weaknesses of the present standard, P2/6 based-evaluation of the contribution of DSR is fully justified as ER P2/6 is the existing network standard and only available framework for quantifying capacity contribution of DSR.

In highly reliable networks the ELCC, EFC and ENC methods allocate much lower contribution to DSR and hence would result in lower increase of Group Demand when compared with P2/6. ENC method and P2/6 produce similar contributions in networks with low reliability (for example, failure rate of 20% and MTTR of 240 hours). Furthermore, the ELCC, EFC and ENC contributions reduce with (i) increase in penetration level of DSR and (ii) with coincidence in delivery (e.g. common mode failure).

EENS is relatively constant for ELCC, EFC and ENC approaches when compared with the P2/6 approach and the EENS for the P2/6 approach depends significantly on (a) the volume of DSR when compared with the size of Group Demand and (b) the existence of common mode failure - effects that are ignored in the P2/6 approach. In this context, the reliability of the network with DSR, when capacity credit is determined by the P2/6 approach, is significantly lower than compared with other methods for deriving DSR capacity value, particularly in highly reliable networks. For example, in the case of the circuit failure rate being 2%, MTTR being 24 hours and with three DSR facilities, the EENS is more than 15 times larger than ENC method. In networks with lower circuit reliability these differences are much smaller.

Given the key objective of this work, focused on assessing the reliability of distribution network when DSR is used to defer network upgrades driven by load growth, the following recommendations are drawn:

- When applying the P2/6 approach to quantifying the contribution of DSR to security of supply, it is important to assess the implication on distribution system reliability performance, particularly in the context of the Interruption Incentive Scheme; in this context, the alternative methods for quantifying capacity contribution of DSR implemented in this work (ELCC, EFC and ENC) would provide useful insights;
- Consideration of diversity and common mode failures of DSR may be relevant when using DSR to substitute for network reinforcement;
- Contractual redundancy improves the probability of delivering the P2/6 contribution and it may be considered in the context of enhancing reliability of supply delivered to end customers and increasing robustness against common mode failures;
- When evaluating the contribution to security of supply of DSR, relative volume of DSR in the context of the size of Group Demand should be considered.

The main learning points resulting from the network-centric reliability modelling are summarised below.

- The P2/6 approach ascribes the same contribution to security of supply to distributed generation irrespective of the network setting, whereas using the EFC, ELCC and ENC approaches the contribution to security of supply varies significantly with respect to the supplying circuit reliability;
- Expected energy not supplied does not change significantly due to high circuit availability, i.e. the probabilities of N-1 and N-2 circuit conditions are small;
- Probability of demand-led DSR delivering contribution estimated by the P2/6 approach increases significantly when additional sites are contracted; with N-1 and N-2 facilities redundancy the probability of supplying Group Demand is high for high availability of circuits;
- EFC and ELCC approaches are more robust than the ENC approach with regards to the network reliability;
- DSR number, penetration level and coincidence in delivery significantly influence the contribution to security of supply;
- P2/6 contribution to security of supply can result in high impact events when the network circuit performance is low, but this impact can be reduced by reducing repair time.

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References