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Economically efficient distribution network design

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Abstract: Decarbonisation of electricity sector, potential increase in electricity demand driven by incorporation of segments of heat and transport sectors, and conditional asset replacement drive the desire for cost-effectiveness of the use of existing assets and use of non-network solutions. A Working Group is tasked to review present and, if needed, propose a new security of supply standard. This study reports on the part of work carried within review. It describes drivers and objective for review, used analytical methodology, and relevant drivers. The results of case studies carried out on illustrative high-voltage networks topology show breakeven value of lost load and economically efficient degree of redundancy for different values of drivers. The study concludes with the key findings of the study.

1 Introduction

It is expected that the electricity sector would be significantly decarbonised by 2030, with potentially increased levels of electricity production and demand driven by the incorporation of segments of heat and transport sectors into the electricity system. Delivering the medium and longer-term carbon-emission reduction targets cost effectively will require fundamental review of the historical philosophy of network operation and design. Existing distribution networks, designed in accordance with the historic deterministic standards, have broadly delivered secure and reliable supplies to customers. However, the key issue regarding the future evolution of the standards is associated with the question of cost-effectiveness of the use of existing assets and the role that advanced, non-network technologies and intelligence-based control could play in the future development and delivery of security of supply to consumers.

This paper will report on the part of the work and outputs involving the identification, research, and evaluation of options for a future UK network security standard to potentially succeed Engineering Recommendation P2/6 [1, 2]. The subject addressed within this paper provides an overview of drivers and objective for reviewing the present security standards. In order to address identified potential weaknesses of the present standards, the fundamental cost–benefit analysis was established for assessing the reliability and cost performance of various network designs and emergency operation strategies. The remaining of the paper contains the following sections methodology, case studies, and conclusions.

2 Drivers and objective for review

Electricity distribution networks are capital-intensive systems and timely and economically efficient investments to respond to increased demand for capacity and services are crucial for maintaining efficiency and reliability of supply. The key drivers for the review of the distribution network planning standards include decarbonisation of generation and demand technologies and emergence of smart grid technologies that could reduce the need for network reinforcement by increasing the utilisation of the existing assets and improving the network reliability performance. Furthermore, some of distribution network assets may be approaching the end of their useful life and may need to be replaced in coming years/decades.

There are a number of identified potential weaknesses of the present standards. These are described below.

Deterministic: The degree of security provided by the deterministic security criteria, using generic rules applied to all conditions, may not be optimal in individual instances (the standard however does allow a departure from defined level of security subject to detailed risk and economic studies). It should be noted that the deterministic nature of P2/6 constitutes also a strength, in terms of simplicity and transparency.

Binary approach to risk: System operation in a particular condition is considered to be exposed to no risk at all or to unacceptable level if the occurrence of faults, from a preselected set of contingences, do not violate or violate the network operational limits, respectively. Distribution network operators (DNOs) recognise this and have practices to accommodate supply risks that remain even when a system is compliant with the security standard.

Redundancy: In many cases, asset redundancy may not be a very good proxy for actual security delivered. In this context, it is important to recognise that deterministic standards assume that all contingencies are equally likely.

Impact of common mode failures: Present standard does not consider common mode failures and high impact low probability events.

Non-network technologies providing network capacity: There is a significant potential for incorporating non-network solutions (such as flexible generation and demand, new storage technologies, dynamic line rating, automatic network monitoring and control based on new information and communication technology etc.) in the operation and design of future distribution networks.

Smart network control and user-driven choice of reliability: At present, network overloads would be managed through demand disconnections, with some of consumers being completely disconnected and some consumers fully supplied. The rollout of smart metering may provide a unique opportunity for smarter management by switching off non-essential loads when network is stressed while keeping supply of essential loads.

3 Methodology

The main objective of this section is to describe the methodology for the economically efficient distribution network design at high-voltage (HV) level. The same principle could be applied to other voltage levels. This analysis focuses on demand growth-driven network upgrade requirements.

Economically efficient distribution network designs are calculated for different drivers: network loading, topology, voltage level and construction, assets failure rate (FR) and upgrade cost, restoration (network reconfiguration and load transfer, mobile and backup generation etc.) and repair times, remote control and automation of switchgear, annual load profile, cost of interruptions, and cost of electrical energy.

3.1 Approach

As the electricity demand may increase in future, this raises a question whether in the short term, it would be economically efficient to upgrade the network following the present security standard or potentially further enhance the utilisation of the existing networks and delay network reinforcement. In order to justify the cost of network upgrade driven by the security requirement, the probabilistic cost–benefits analysis framework for distribution network operation and planning illustrated in Fig. 1 is developed. For each network design option, costs of interruptions, operational measures, and network investment are considered. Cost of interruption represents a measure of the economic losses caused by interruption in the electricity supply. Cost of operational measures is the cost of emergency measures such as the cost of providing backup generation (e.g. rental cost). Cost of network investment includes the cost of upgrading the network.

In order to calculate the cost of interruptions, an analytical approach based on multi-state Markov models is applied. It takes into the account single and overlapping faults, asset maintenance, and restoration processes through fault clearing, network reconfiguration, application of transfer capability of adjacent networks, or use of mobile generation. It is important to highlight that the reliability parameters used in this section, such as FRs, restoration, and repair rates, are based on the long-term average values, not considering exceptional events. The approach is fundamentally similar to the method described in ACE51 [3].

3.2 Cost of interruptions

For the evaluation of economic losses caused by interruptions different customer damage functions (CDFs), for example, expressing the dependency of the cost of interruptions on their duration and unserved energy or customer peak demand, can be used. For various CDFs, equivalent value of lost load (VoLL) values could be determined. Lower values of VoLL will drive lower optimal degree of redundancy. Possible smart demand shedding would drive lower equivalent VoLL and hence optimal degree of redundancy would be lower. A range of studies have been carried out with the aim to estimate the breakeven value of VoLL at which the existing network would be upgraded cost effectively. This enables clear assessment of the optimal degree of redundancy for different customer interruption costs to be determined (that may also correspond to different CDFs). Report by London Economics [4] estimate the VoLL for domestic, small and medium-sized enterprises (SME) and industrial and commercial electricity users, which is used in this analysis. For domestic customers, the statistically significant estimate of the VoLL ranges from £1,651 to 11,820/MWh during Winter peak conditions with a headline figure of £10,289/MWh. For SME, the respective range is from £19,271 to 39,213/MWh for all conditions with a headline figure of £35,488/MWh and for industrial and commercial customers, the overall value is about £1,400/MWh. They have derived the load-share weighted average VoLL across domestic, and small and medium enterprise users for winter peak weekday as £16,940/MWh (the same values are used in the development of capacity market, as a part of Electricity Market Reform, considered by DECC). VoLL of £17,000/MWh is used in this study as the central value and to assess the sensitivity and robustness of identified solutions the analysis using larger value of VoLL (£34,000/MWh) is carried out.

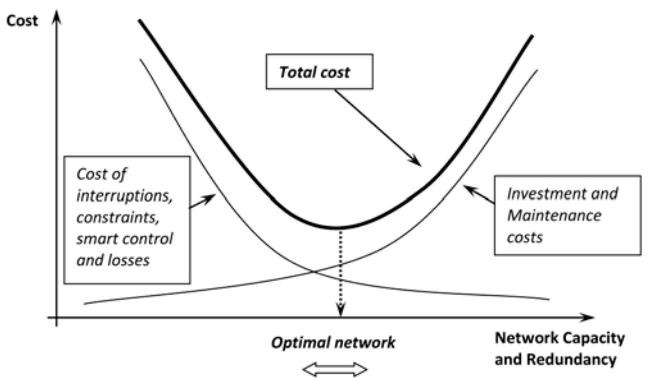

Fig. 1 *Probabilistic cost–benefits analysis framework for distribution network operation and planning*

3.3 Breakeven VoLL

The breakeven VoLL, at which the network upgrade is economically justified for different levels of network redundancy, is defined when the savings from reduced EENS, losses, and cost for renting mobile generation are equal to the cost of network upgrade to comply with the present security standards. If the equivalent VoLL is less than the breakeven VoLL, network upgrade is not economically efficient and vice versa.

3.4 Economically efficient degree of redundancy

Economically efficient degree of redundancy is defined as degree of redundancy for which breakeven VoLL is equal to the specified VoLL.

4 Case studies

A range of studies has been carried out to investigate the cost-effectiveness of the present security standards on HV networks. Moreover, sensitivity studies have been performed to investigate the impact of the selected parameters on the optimal degree of network redundancy. Parameters used in the sensitivity studies include network load, construction type, e.g. overhead (OH) or underground (UG), network FRs, restoration and repair times, network upgrade costs, the presence of emergency supplies, and VoLL.

Fig. 2 shows the generic configuration of a radial HV network with a normally open point that provides an alternative infeed if a fault occurs at one of the feeders. This configuration is used in the studies to evaluate the cost of having different levels of redundancy, namely: N-0.75, N-0.5, N-0.25, N-0 by increasing the load connected to the test network. For example, if the peak load of the HV feeder is initially 2 MW and the network is N-1 compliant, it would mean that after any one component out of service, network would be able to supply demand in peak condition, including for an outage at the beginning of one of

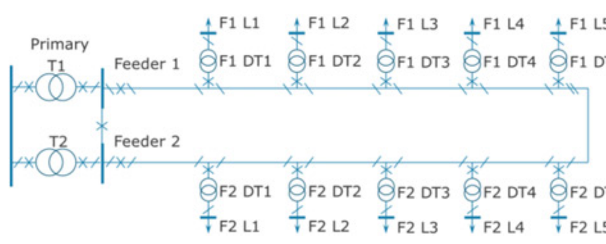

Fig. 2 *HV network case studies*

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feeders. Hence for N-0 compliant network, the peak load of the feeder can be doubled (i.e. 4 MW which is equal to the rating of the feeder) without need for any network reinforcement. This notation is generalised to represent non-integer degree of redundancy. Increasing the load per feeder by 500 kW (total load per feeder is 2.5 MW) means the degree of redundancy becomes N-0.75. Similarly applies for the N-0.5 and N-0.25 cases. For the N-0 case, all capacity is needed to accommodate the peak demand, i.e. there is no spare capacity. However, during off-peak condition, there would still be spare capacity at the time of fault and only for some of faults proportion of customers may experience longer interruptions.

When a fault occurs on a section, for example, on feeder 1 section between F1 DT1 and F1 DT2, feeder circuit breaker will open to break fault current and supply to load points F1 L1 to F1 L5 will be interrupted. The process of locating the faulty section and its isolation will then start. The use of automation, remote control, and manual switching in which the section at fault is located and isolated are considered. After that, a supply is restored to F1 L1 by switching on the feeder circuit breaker. For manual switching, it is assumed that, in the first stage, customers whose supply is restored would experience outage of 30 min. Supply for F1 L2 to F1 L5 is restored through a backfeed by closing the NOP located next to F1 DT5. Manual switching of NOP is assumed to take on average 20 min. This means that the customers whose supply is restored from the backfeed would experience outage of 50 min. These times are on average 10 and 2 min for remote control and automation, respectively. After that, all load points will be resupplied and the repair process could start. The non-urgent repair time is, on average, 5 days for HV circuits. If during the repair process, an overlapping fault occurs, for example, on feeder 1 section between F1 DT4 and F1 DT5, feeder 2 circuit breaker will open, and all load connected to feeder 2 and loads F1 L2 to F1 L5 will lose supply. The section with the fault will be isolated by opening the relevant switchgear and all load points connected to feeder 2 and F1 L5 will be resupplied from feeder 2. Load points F1 L2 to F1 L4 will still be out of supply. This would then trigger urgent repair to be carried out. For HV UG circuits, the urgent repair time varies between 6 and 18 h. In order to speed-up the restoration of supply at load point F1 L2 to F1 L4, it is assumed that a mobile generation would be provided within 3–6 h.

Table 1 shows the combination of reliability parameters of HV UG cables and OH lines used in the studies. The FRs, mean time to restore, mean time to repair, and upgrade costs of HV network are the key parameters that drive economically efficient network redundancy. It is found that the results are not sensitive to the section lengths as the cost and the FR increase linearly with the increase in length, which cancels out the effect of increasing section length. The values are selected from analysing data of the quality of supply over 5 year periods from different DNOs [5].

It is assumed that feeders are not tapered and that a minimum number, depending on degree of redundancy, of sections would need to be upgraded, for example: for N-0.75 four sections (two per feeder), for N-0.5 six sections, and for N-0.25 and below, all sections. Load shedding is carried out if asset is loaded above nameplate rating. The calculated breakeven VoLLs for different load profiles including losses are presented in Table 2. The values of breakeven VoLLs are written in blue or green if they are less than or equal to £17,000 and £34,000/MWh, respectively.

For high reliability networks, with FRs of 2%/km year and restore/repair times of 3 and 24 h, respectively, the VoLL that would justify reinforcement from degree of redundancy of N-0.75 to N-1 would need to be between £3,576,921 and £64,859,361/MWh. This reinforcement would be clearly inefficient as the values are much higher than the reference value of VoLL of £17,000/MWh that is used in this study. The breakeven VoLL decreases when the network is less reliable, characterised by higher FR and MTTR. For example, for the case of N-0.5 degree of redundancy and load profile with high load factor, FR of 10%, MTTR of 24/24, the breakeven VoLL for the low and high upgrade cost scenarios are £13,927 and £24,548/MWh, respectively. This means the upgrade is justified if the VoLL is £34,000/MWh. A higher VoLL leads into increased demand for system redundancy.

Sensitivity studies have been carried out to investigate the impact of peak demand (group demand) with initial feeder peak load of 500 kW and 5 MW. Breakeven VoLLs for sensitivity studies and OH networks are not presented in this paper due to space limit. The findings from studies support conclusion that the drivers for higher degree of redundancy are high VoLL, high FR (less reliable

Table 1 HV network reliability parameters and range of upgrade costs

Asset category	Failure rate, %/km year	Mean time to restore/repair, h	Range of upgrade cost, £/km
OH	5 and 20	3, 6, and 24/24	24,000–36,000
UG	2 and 10		88,000–132,000

Table 2 Breakeven VoLL (£/MWh) for HV UG feeders with the initial feeder load of 2.5 MW; low load factor is 45% and high 65%

Degree of redundancy	Failure rate, %/km year	MTT restore/repair, h	Low load factor		High load factor	
			Low upgrade cost	High upgrade cost	Low upgrade cost	High upgrade cost
N-0.75	2	3/24	40,686,822	64,859,361	3,576,921	6,114,226
	2	6/24	20,088,394	32,023,154	1,780,879	3,044,153
	2	24/24	4,833,156	7,704,408	442,491	755,949
	10	3/24	10,196,137	16,255,357	733,764	1,257,097
	10	6/24	4,749,106	7,571,340	362,799	621,554
	10	24/24	967,797	1,542,740	88,605	151,372
N-0.5	2	3/24	7,295,924	11,779,032	555,781	982,839
	2	6/24	3,628,987	5,858,882	277,037	489,910
	2	24/24	897,865	1,448,965	69,549	122,591
	10	3/24	1,533,341	2,479,705	108,683	194,780
	10	6/24	753,182	1,218,040	54,089	96,938
	10	24/24	179,790	290,143	13,927	24,548
N-0.25	2	3/24	3,085,006	4,909,514	363,291	620,179
	2	6/24	1,536,852	2,445,765	181,107	309,171
	2	24/24	383,698	609,776	45,899	77,829
	10	3/24	618,198	989,363	68,165	119,762
	10	6/24	306,834	491,057	33,958	59,661
	10	24/24	76,832	122,102	9,191	15,585
N-0	2	3/24	1,038,007	1,691,831	156,183	283,275
	2	6/24	517,481	843,433	77,884	141,261
	2	24/24	130,336	211,568	20,002	35,811
	10	3/24	200,284	332,053	27,620	53,113
	10	6/24	99,699	165,292	13,768	26,476
	10	24/24	26,099	42,365	4,005	7,171

Table 3 Sensitivity to the breakeven VoLL' that justifies different levels of redundancy to the smart management of network overloads using disconnection of non-essential loads

Network reliability	Security level	Breakeven VoLL (without smart management of overloads)	Breakeven VoLL (with smart management of overloads)
low	N-0.75	8,800	875,000
	N-0.5	3,400	182,100
	N-0.25	1,500	59,000
	N-0	700	21,500
medium	N-0.75	44,400	4,375,000
	N-0.5	32,300	1,275,000
	N-0.25	7,600	312,500
	N-0	3,500	113,300
high	N-0.75	90,200	9,296,900
	N-0.5	35,400	1,961,500
	N-0.25	15,200	625,000
	N-0	7,400	229,700

network), high MTTR (long restauration and repair times), low upgrade cost (cost of reinforcing OH is lower than the cost for UG networks). The studies also provide evidence that the present security standards may be optimal for OH with low reliability and high demand, but may be too conservative against other cases, e.g. highly reliable UG networks.

The finding that P2/6 prescribes economically inefficient levels of network redundancy still holds when accounting for the role of non-network solutions. As Table 3 shows, when DNOs have the ability to manage network overloads through disconnection of *non-essential load*, such as through customers being willing to offer demand side response services to DNOs, the breakeven VoLL required to justify redundancy of network assets rises materially.

This suggests that the levels of reliability that it is economically efficient for DNOs to provide using network investments may change markedly depending on the degree to which the load they serve is flexible. This evidence shows that the prospect of DNOs increasing the use of smart network management to address constraints reinforces the conclusion that the current levels of reliability required by P2/6 are higher than the economically efficient levels.

Table 4 Optimal degree of redundancy for HV networks; 'N-' term is omitted for simplicity

	FR, %/km year	MTTR, h	Feeder N-1 peak demand, kW		
			500	2500	5000
overhead	5	3/24	0 0	0 0:0.75/0.25:0.75	0 0.25:0.75/0.5:0.75
		6/24	0 0	0 0.25:0.75/0.5:0.75	0:0.25 0.5:0.75/0.5:1
		24/24	0 0:0.25/0:0.5	0:0.25/0:0.5 0.5:1	0:0.5/0.25:0.5 0.75:1
	20	3/24	0 0:0.25	0:0.25 0.5:1	0:0.25/0.25:0.5 0.5:1/0.75:1
		6/24	0 0:0.25/0.25:0.5	0:0.25/0.25:0.5 0.5:1/0.75:1	0.25/0.25:0.5 0.75:1
		24/24	0/0:0.25 0.5:0.75	0.25:0.5/0.5:0.75 1	0.5:0.75 1
underground	2	3–6/24	0 0	0 0	0 0
		24/24	0 0	0 0:0.25	0 0:0.25/0.25:0.5
	10	3/24	0 0	0 0	0 0/0:0.25
		6/24	0 0	0 0/0:0.25	0 0:0.25/0.25:0.5
		24/24	0 0	0 0.25:0.5/0.5:0.75	0/0:0.25 0.5:0.75

5 Optimal degree of redundancy

The breakeven VoLLs have been analysed to derive the optimal degree of redundancy for HV networks. This analysis determines the maximum loading of the networks before the upgrade can be justified and the results are shown in Table 4. The results are given for different initial feeder peak demands (demand groups), i.e. 500 kW, 2.5, and 5 MW. The initial feeder peak demand is half the circuit capacity. Two VoLL thresholds are used, as in the previous tables, i.e. £17,000 and £34,000/MWh. The optimal degree of redundancy in Table 4 is coded for two values of VoLL separated with '/' as follow. For example, 0:0.25/0.25:0.5 means that the optimal degree of redundancy is between N-0.25 and N-0 for VoLL of £17,000/MWh and is between N-0.5 and N-0.25 for VoLL of £34,000/MWh. Upper values in table cells are for load profile with low load factor and lower values for load profile with high load factor. The difference between optimal degrees of redundancy is up to ~0.5–0.75 for OH networks and up to ~0.25–0.5 for UG networks for higher network loading. This implies that when the VoLL is 17,000/MWh, it will be justified to increase the load, for high load factor, by 75% (N-0.25) to 100% (N-0). If VoLL is £34,000/MWh, it will be justified to increase the load by between 50% (N-0.25) and 75% (N-0.25) before the upgrade is necessary. If there is no '/', the value is valid for both VoLL thresholds.

6 Conclusion

The present security standards tend to be conservative, dealing with worst-case scenarios. This implies that the present security standard would be cost-effective only for 'extreme' cases with high FRs, long restore/repair times, and low upgrade costs. In most cases, however, particularly at the HV level, the existing networks could accommodate demand growth in the short term, relaxing the N-1 requirement up to the point where the reinforcement becomes economically justified. For reliable HV networks, with low FR and low restore/repair times, the peak load can nearly be doubled without the need for network reinforcement.

The optimal level of network redundancy is case-specific, depending on many parameters (reliability characteristics, investment cost, cost of supply interruptions, mitigation measures), and therefore, it may be difficult to implement 'one size fits all' standard with the expectation to be cost-effective in all cases. On the other hand, implementation of a deterministic standard could deliver simplicity and transparency, which are very important, particularly for customers to clearly understand the investment decisions that DNOs make. Networks with low reliability performance (i.e. higher FRs, longer time to restore or repair), low upgrade cost, and high outage costs (high VoLL) tend to require a higher degree of redundancy compared with networks with relatively higher reliability, higher upgrade cost, and lower outage cost.

For networks supplying larger demand groups, higher degree of redundancy is found to be efficient. Although this trend is consistent with the present standard, it does not necessarily validate the efficiency of the present standard. The requirements for network upgrade due to demand growth are also lower when corrective measures such as mobile generation and load-transfer capability are used.

Enhancing the utilisation of the existing network will in turn degrade the service quality, potentially increasing customer interruptions, customer minutes lost, and energy not supplied. Customers' expectations in any decision need to be considered. The analysis demonstrated that it is still beneficial (in financial terms) to defer the investment if possible. It is worth mentioning

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that the VoLL for some HV UG network with high reliability and high upgrade cost may need to be more than £3,500,000/MWh, to maintain N-1 degree of security. Furthermore, further investment in network automation, real-time monitoring, and control equipment may be beneficial and could further enhance reliability performance and the utilisation of existing assets.

7 Acknowledgments

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