LONG-TERM ECONOMICALLY EFFICIENT DESIGN OF LOW AND MEDIUM VOLTAGE DISTRIBUTION NETWORKS

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ABSTRACT

The envisaged load growth and ageing of assets require optimal distribution network replacement strategies. Losses inclusive network design results in network capacity significantly larger than the peak demand requirements. Given significant future low and medium voltage network spare capacity, in this paper, the potential for cost-effective incremental enhancement of security of supply is investigated. The analysis shows that long-term economically efficient design of low voltage networks and underground medium voltage networks is N-1. The range of economically efficient designs of overhead medium voltage networks is observed, from N-0 for reliable networks with low loading to N-1 for unreliable networks with high loading at value of lost load of £17,000/MWh.

INTRODUCTION

Electricity demand is expected to increase in the long term due to the connection of new consumers and the envisaged electrification of transport and heat sectors. In addition, many assets installed in the ’70s or before are approaching the end of their useful life, driving the need for replacements. These factors are expected to drive the future development of electricity networks.

Network losses are one of the critical factors to be considered in planning the capacity and design of future distribution networks. Previous work [1] demonstrated that the distribution network capacities should be significantly larger than the peak demand requirements given that the long-term savings in losses exceed the extra cost of oversizing the network. For example, previous studies [2] showed that an optimally sized low voltage (LV) cable, considering the capitalisation guidelines in [3] would be operated at maximum demand no higher than 12-25% of its thermal rating, as indicated in Table 1. Similarly, a medium voltage (MV) overhead (OH) line would be subject to a maximum loading no higher than 13-21% of its thermal rating. As a comparison, the current level of peak loading according to the UK’s Engineering Recommendation P2/6, other than for LV, is typically 50% [4][5] indicating the need to include losses consideration in the future distribution network planning.

As the loss-inclusive network design would provide significant spare capacity, this may be used to improve the security of supply at low costs through increasing network connectivity. The objective of this paper is to determine the optimum redundancy levels for distribution networks in the long term. It attempts to answer the question whether the future MV and LV networks should continue to be designed at N-1 and N-0 security levels, respectively, and whether there is a case for enhancing the security beyond N-1 for MV and beyond N-0 for LV. The work presented in this paper is part of the work carried out in [2].

Table 1: Losses-driven optimal network capacity

Asset		Economically efficient maximum network loading (%)
Cables	LV	12 - 25
	MV	14 - 27
OH lines	LV	11 - 19
	MV	13 - 21

The following sections describe the results of comprehensive studies looking at alternative design philosophies of distribution networks at various voltage levels, with the objective to determine the least-cost design and level of redundancy (or security) considering the significantly increased capacity of future networks. The approach is described in [6].

LV NETWORK DESIGN

A range of studies has been carried out to determine the long-term economically efficient LV network design, looking at a range of deterministic security levels considering different degrees of redundancy, i.e. N-0, N-1 and ‘N-1.5’. A generic LV system shown in Figure 1 is used to evaluate the performance of various configurations with different levels of redundancy in order to determine the optimal configuration producing the least-cost solution.

The network configuration coloured in blue represents the network without any redundancy (N-0). In this configuration, a loss of one circuit component will result in a loss of supply for the entire LV feeder. If an additional link is added at the end of the feeder (the green line/cable), the new configuration allows the demand to be supplied from another feeder. This configuration allows N-1 redundancy level to be achieved if the fault is not at distribution transformer.

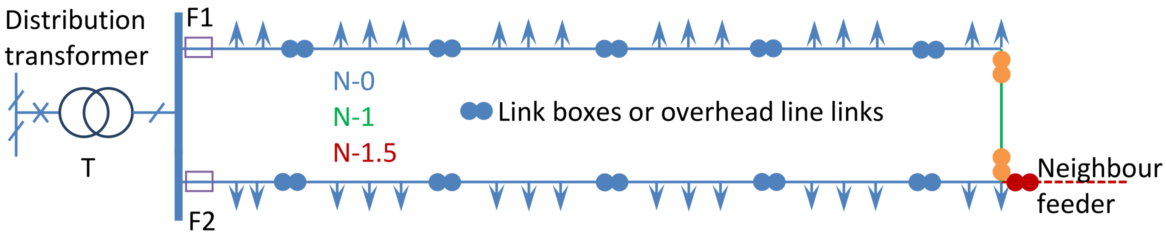

Figure 1: A generic LV network system with different configurations to provide certain levels of security of supply

By adding a connection to an adjacent feeder (the red line/cable) on top of the N-1 secure configuration, the redundancy level can be improved to 'N-1.5'. In this case, there will be no loss of supply even with two simultaneous outages if the outages occur at different feeders. The loss of supply will occur if the two outages occur at the same feeder. Thus, this configuration is more secure than N-1 but less secure than N-2. Therefore, it is classified as a 'N-1.5' configuration.

Table 2 shows the assumptions on reliability and cost parameters used in the studies. The key parameters used in the studies are the failure rate, supply restoration time, fault repair time, network loading, network cost (assumed proportional to section length), and Value of Lost Load (VoLL) [7][8][9]. Different sets of parameters are used to develop high and low circuit availability scenarios for UG cables and OH lines.

Table 2: Reliability parameters for LV studies

Parameter	Value
Type of network	OH lines and UG cables
Feeder peak demand (kW)	10, 50 and 100
Failure rate (%/km.year)	10 and 50
Supply restoration time (h)	3, 4 and 8
Fault repair time (h)	4 and 8
Feeder length (km)	0.75
VoLL (£/MWh)	17,000
Cost	Link boxes: £1.5k Line links: £0.75k

Table 3 and Table 4 show the results of the study for LV OH and underground (UG) networks, respectively. The table contains the optimal long-term redundancy levels for different LV network constructions, failure rates, restore and repair times, and feeder peak loadings. The results from the table should be interpreted as follows: N-0 means that N-0 redundancy is the optimal redundancy level if the VoLL is £17,000/MWh. The variation of the costs of link boxes and line links investigated in the study was ±20% of the values specified in Table 2.

The results demonstrate that the N-0 design is economically efficient for OH networks with very low demand and high availability. When lower loading levels are combined with relatively lower availability, as well as when higher loading levels are encountered, the N-1 design is economically efficient. For UG networks the economically efficient design is predominantly N-1, as it is expected to typically supply higher levels of load. The key drivers giving rise to the N-1 design are higher loading, higher failure rates and longer restoration/repair times as well as the greater VoLL.

Table 3: LV OH network long-term planning optimal redundancy; N-0 denotes that for the VoLL of £17,000/MWh economically efficient redundancy is N-0; fault repair time 4 hours

Failure rate (%/km.year)	Supply restoration (hours)	Feeder Peak Demand (kW)		
		10	50	100
10	3	N-0	N-1	N-1
	4	N-0	N-1	N-1
50	3	N-1	N-1	N-1
	4	N-1	N-1	N-1

The results in Table 3 demonstrate that in most cases N-1 design, for LV OH networks, is economically efficient except for very low demand and high availability. When lower loading levels are combined with relatively lower availability, as well as when higher loading levels are encountered, the N-1 design is economically efficient.

Table 4: LV UG network long-term planning optimal redundancy; fault repair time is 8 hours

Failure rate (%/km.year)	Supply restoration (hours)	Feeder Peak Demand (kW)	
		50	100
10	3	N-0:N-1	N-1
	8	N-1	N-1
50	3	N-1	N-1
	8	N-1	N-1

The results in Table 4 demonstrate that for UG networks the economically efficient design is predominantly N-1, as it is expected to typically supply higher levels of load. LV network may continue to operate radially but may be reconfigured when needed (post-fault).

The key drivers giving rise to the N-1 design are higher loading, higher failure rates and longer restoration/repair times as well as greater VoLL.

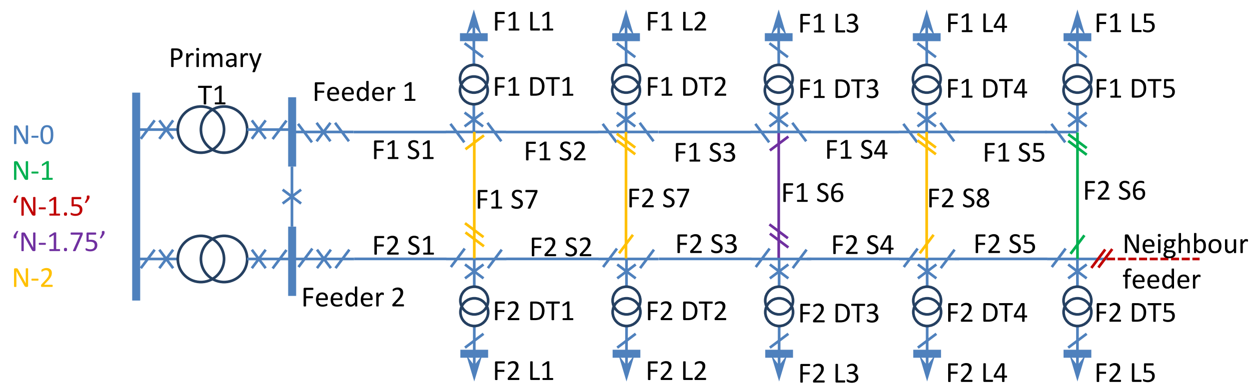

Figure 2: A generic MV network system with different configurations to provide certain levels of security of supply

MV NETWORK DESIGN

A generic MV system shown in Figure 2 is used to evaluate the performance of various configurations with different levels of redundancy in order to determine the optimal configuration producing the least-cost solution. A range of studies has been carried out to determine the long-term economically efficient MV network design looking at a range of deterministic security levels such as N-0, N-1, 'N-1.5', 'N-1.75', and N-2 as shown in Figure 2.

The starting MV network topology is radial (N-0), coloured in blue. Fault at one of the sections will result in a loss of supply to some consumers until the component is repaired or an alternative source of supply is arranged. Connecting the feeders at their ends, as shown in green, and keeping one of the switchgears open allows supplying some of the load affected in the case of a fault at one feeder from the remaining feeder. The prerequisite for that is that there is enough feeder capacity to supply additional load, which is indeed expected to materialise in the case of loss-inclusive design. With this configuration, an N-1 redundancy level is achieved given that the whole load can be supplied after network reconfiguration following a single section outage. An outage of a ring main unit results in a loss of supply to the corresponding load that cannot be restored by reconfiguring MV feeders.

Providing a normally open connection from one of the feeders to a neighbouring feeder (coloured in red) allows for the restoration of supply for some of the affected load even in the case of double overlapping outages, such as an outage of one section of feeder 1 and one section of feeder 2. This configuration is denoted as 'N-1.5'. Adding another mid-point normally open connection, coloured purple, makes it possible to restore supply by feeder reconfiguration even for some overlapping faults on the same feeder. This topology is therefore denoted as 'N-1.75'. The last considered configuration, obtained by adding three Normally Open Point (NOP) sections coloured in orange, is denoted as N-2, as in this configuration the supply can be restored though reconfiguration for almost any double overlapping fault.

Table 5 shows the assumed reliability and cost parameters for the MV network used in the study. Key parameters that have been varied are the failure rate, supply restoration time, fault repair time, network loading, network cost (assumed proportional to section length) and VoLL.

Table 5: Reliability parameters for MV studies

Parameter	Value
Type of network	OH lines and UG cables
Feeder peak demand (kW)	500, 2500, and 5000
Failure rate	OH line 1km: 5% and 20% UG cable 1km: 2% and 10%
Supply restoration time (h)	3 and 12
Fault repair time (h)	24 and 120
Section length (km)	0.25 and 1
VoLL (£/MWh)	17,000
Cost	OH line 1km: £19k UG cable 1km: £101k PM switchgear: £2.9k GM switchgear: £8k

Table 6 to Table 9 show the *breakeven length* of NOP sections for OH and UG feeders and for different loading conditions. The breakeven length of NOP sections is obtained by calculating the benefit of investing in NOP sections calculated as savings in EENS and then determining the length of the section that would result in an investment cost equal to the benefit of the section. The incremental benefit is obtained from the incremental savings in Expected Energy Not Supplied (EENS) due to security improvement, multiplied by the VoLL. For example, for the OH feeders with failure rate 20%/km.year, supply restoration and fault repair times of 12 and 120 hours respectively and section lengths of 0.25 km, the potential benefit of improving the security level from N-0 to N-1 is £94,306/year if the VoLL is £17,000/MWh (Table 6). Depending on the assumed cost of new OH lines and switchgear, the length of the NOP section should be less than 18.3 km in case of high asset costs, or 27.5 km in case of low asset costs, for the N-1 configuration to be more cost-efficient than N-0. The cost of two switchgears is deducted from this benefit, and the remaining benefit is divided by the unit cost of the conductor. The result is the length of the NOP section for which the total cost of N-0 and N-1 designs is the same and is denoted as breakeven length. If the actual NOP section length is shorter than the breakeven length, the economically efficient configuration is N-1, otherwise. it is N-0. For the purpose of this exercise, it is assumed that the required NOP section length would be the same as the length of the main feeder sections. Breakeven NOP section lengths printed in blue denote that the section length is shorter than the breakeven length, while red denotes the opposite. For sensitivity purposes, it is assumed that the asset costs can vary ±20% from the values given in Table 5.

Table 6 and Table 7 show the breakeven lengths of NOP sections for MV OH feeders with a peak demand of 2,500 kW and 500 kW respectively. For all considered combinations it is at least N-1 configuration that is the most efficient. For relatively unreliable MV OH networks and with section lengths of 1 km the N-1.5 design is economically efficient if asset cost is low. The incremental benefit is linearly dependent on feeder loading, which can be verified by comparing the benefits in Table 6 and Table 7.

Table 6: Breakeven length of NOP sections for which cost of the upgrade is the same as a potential benefit for MV OH feeders for different failure rate and mean time to restore and repair and when each feeder peak demand is 2,500kW

Failure rate (%/km. year)	Restore /repair (hours)	Section length (km)	Configuration	Incremental benefit @ £17,000/MWh (£/year)	Breakeven length of NOP section (km)	
					Min assets cost	Max assets cost
5	3/24	0.25	N-1	**£5,904**	**1.6**	**1.0**
		1	N-1	**£23,574**	**6.8**	**4.5**
	12/120	0.25	N-1	**£23,792**	**6.8**	**4.5**
		1	N-1	**£94,306**	**27.5**	**18.3**
20	3/24	0.25	N-1	**£23,574**	**6.8**	**4.5**
		1	N-1	**£93,616**	**27.3**	**18.2**
	12/120	0.25	N-1	**£94,306**	**27.5**	**18.3**
		1	N-1	**£363,594**	**106.6**	**71.0**
			N-1.5	**£10,310**	**2.9**	**1.9**
			N-1.75	**£2,474**	**0.6**	**0.3**

Table 7: Breakeven length of NOP sections for which cost of the upgrade is the same as a potential benefit for MV OH feeders for different failure rate and mean time to restore and repair and when each feeder peak demand is 500 kW

Failure rate (%/km. year)	Restore /repair (hours)	Section length (km)	Configuration	Incremental benefit @ £17,000/MWh (£/year)	Breakeven length of NOP section (km)	
					Min assets cost	Max assets cost
5	3/24	0.25	N-1	**£1,181**	**0.2**	**0.1**
		1	N-1	**£4,715**	**1.2**	**0.8**
	12/120	0.25	N-1	**£4,758**	**1.3**	**0.8**
		1	N-1	**£18,861**	**5.4**	**3.6**
20	3/24	0.25	N-1	**£4,715**	**1.2**	**0.8**
		1	N-1	**£18,723**	**5.4**	**3.5**
	12/120	0.25	N-1	**£18,861**	**5.4**	**3.6**
		1	N-1	**£72,719**	**21.2**	**14.1**
			N-1.5	**£2,062**	**0.5**	**0.3**

Given that distances between distribution transformers in this network are on average 0.25 km, similar length is assumed to be required for a new NOP section, and hence the net benefit can be derived from moving to the N-1 configuration given that the required length is shorter than the breakeven length. In the case of 1 km, average distances between distribution transformers the assumption is that the NOP section would be also 1 km. Increasing further the level of redundancy to N-1.5 is not economically justifiable considering that the potential benefit of the N-1.5 configuration over N-1 is smaller than the cost of the two additional switchgears required to implement the N-1.5 configuration. It can be concluded that the N-1 configuration is the optimal and economically efficient design for this case. This approach is then applied to other cases with different section lengths, failure rates, etc. Switching duration does not impact the breakeven length of NOP sections significantly, and therefore the conclusions derived here apply for both automated fault isolation and manual switching. It is further observed that the time required for feeder reconfiguration does not impact the results significantly.

In Table 7, for the case with the failure rate of 5%/km.year, restore/repair times of 3/24 hours and a section length of 0.25 km, the incremental benefit of the N-1 configuration compared to N-0 is £1,181/year for the VoLL of £17,000/MWh. The breakeven length of the NOP section, ranging between 0.1 and 0.2 km depending on the asset costs, is always smaller than the feeder section length. It is therefore concluded that N-0 is the economically efficient design in this case.

In the case of 1 km section length but with the same failure rates and restore and repair times, the breakeven length is between 0.8 and 1.2 km. This means that for a higher level of new asset cost the economically efficient solution is N-0, while for a lower asset cost one should follow the N-1 design. For all other cases in Table 7, the economically efficient solution is the N-1 design.

Table 8 shows the breakeven length of NOP sections for MV UG feeders where the feeder peak demand is 2,500 kW.

Table 8: Breakeven length of NOP sections for which cost of the upgrade is the same as the potential benefit for MV UG feeders for different failure rate and mean time to restore and repair when each feeder peak demand is 2,500 kW

Failure rate (%/km. year)	Restore /repair (hours)	Section length (km)	Configuration	Incremental benefit @ £17,000/MWh (£/year)	Breakeven length of NOP section (km)	
					Min assets cost	Max assets cost
5	3/24	0.25	N-1	**£2,363**	**0.1**	**0.0**
		1	N-1	**£9,443**	**0.9**	**0.6**
	12/120	0.25	N-1	**£9,534**	**0.9**	**0.6**
		1	N-1	**£37,998**	**4.2**	**2.7**
20	3/24	0.25	N-1	**£11,801**	**1.2**	**0.7**
		1	N-1	**£47,034**	**5.2**	**3.4**
	12/120	0.25	N-1	**£47,440**	**5.2**	**3.4**
		1	N-1	**£186,327**	**21.0**	**14.0**

The key difference between UG and OH networks in terms of the breakeven length of NOP sections arises from the fact that UG network is generally more expensive than OH. From Table 5 the UG cable is about five times more expensive, and the two switchgears are more than five times more expensive than for an OH line. On the other hand, the UG network generally has greater availability. In UG networks with a failure rate of 2%/km.year, supply restoration and fault repair times of 3 and 24 hours, respectively, and a section length of 0.25 km, the economically efficient design is N-0 given that EENS savings (£2,363) are not enough to even cover the cost of switchgears for VoLL of £17,000/MWh. For relatively low failure rates the economically efficient design is N-0 in short networks where the cost of new assets is towards the top of the considered range. For all other considered combinations, the economically efficient design is N-1. The incremental benefit again increases proportionally to the increase of peak demand. Given that the highest considered failure rate of UG networks is half of that of OH networks and that the UG network is more expensive to build, there are no economically efficient designs observed beyond N-1.

Table 9 shows the breakeven lengths of NOP sections for UG networks when the peak demand per feeder is 5,000 kW. In virtually all considered configurations the N-1 design is the most economically efficient. The only exception is for short feeders with a failure rate of 2%/km.year, supply restoration and fault repair times of 3 and 24 hours, respectively, and high asset cost, where N-0 is the preferred design.

Table 9: Breakeven length of NOP sections for which cost of the upgrade is the same as a potential benefit for MV UG feeders for different failure rate and mean time to restore and repair when each feeder peak demand is 5,000 kW

Failure rate (%/km. year)	Restore /repair (hours)	Section length (km)	Configuration	Incremental benefit @ £17,000/MWh (£/year)	Breakeven length of NOP section (km)	
					Min assets cost	Max assets cost
5	3/24	0.25	N-1	**£4,725**	**0.4**	**0.2**
		1	N-1	**£18,886**	**2.0**	**1.3**
	12/120	0.25	N-1	**£19,068**	**2.0**	**1.3**
		1	N-1	**£75,995**	**8.5**	**5.6**
20	3/24	0.25	N-1	**£23,602**	**2.5**	**1.6**
		1	N-1	**£94,069**	**10.5**	**7.0**
	12/120	0.25	N-1	**£94,879**	**10.6**	**7.0**
		1	N-1	**£372,654**	**42.2**	**28.1**
			N-1.5	**£5,193**	**0.4**	**0.2**

CONCLUSIONS

The work presented in this paper concludes that a higher degree of redundancy is generally required in a system which serves a higher demand and characterised by lower network reliability (i.e. higher failure rates and higher supply restoration time) and lower flexibility (e.g. low load transfer capability without mobile units to enable quick restoration), and when the value of security (VoLL) is higher. Another observation is that the UG network tends to require less redundancy due to its higher network reliability and higher network cost.

The results are summarised in Table 10. The N-1 redundancy level is generally adequate for MV networks, although in some cases the network can be planned with an N-0 redundancy level (e.g. in cases with low failure rates, low demands, and fast supply restoration times). The results also indicate that, in line with present security standards (P2/6), higher voltage networks that supply larger demand groups would require a higher level of redundancy.

Table 10 The range of economically efficient degree of redundancy needed at LV and MV networks for VoLL of £17,000/MWh

Voltage level	OH networks	UG networks
LV	N-1	N-1
MV	N-0:N-1	N-1

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REFERENCES

[1] S. Grenard, D. Melovic, G. Strbac, 2003, “Effect of losses on design and regulation of distribution networks,” *CIRED – 17th Intl. Conf. on Electricity Distribution*, Barcelona, Spain

[2] G. Strbac, P. Djapic, et al., 2015, Review of Distribution Networks Security Standards, Extended Report, London, UK

[3] Ofgem, 2017, Guide to the RIIO-ED1 electricity distribution price control, London, UK

[4] ENA, Engineering Recommendation P2/6, 2006

[5] R. Allan, G. Strbac, et al., 2004, *Developing the P2/6 methodology*, Report Number: DG/CG/00023/REP, URN 04/1065

[6] British Electricity Boards, 1979, Report on the Application of Engineering Recommendation P2/5 Security of Supply, A.C.E. Report No. 51

[7] K. Kariuki, R. Allan, 1996, “Evaluation of Reliability Worth and Value of Lost Load”, *IEE Proceedings on Generation Transmission and Distribution*, Vol. 143, 171-180

[8] London Economics, 2013, The Value of Lost Load (VoLL) for Electricity in Great Britain: Final report for OFGEM and DECC, London, UK

[9] Reckon, 2012, Desktop review and analysis of information on Value of Lost Load for RIIO-ED1 and associated work, London, UK