Analysis of Contact-Voltage Losses in Low-Voltage Electricity Distribution Systems of the U.K.

Dr. Eric D. Larson
PI, Energy Systems Analysis Group
Andlinger Center for Energy & Environment
Princeton University, Princeton, NJ, USA

Prof. Minjie Chen
PI, Princeton Power Electronics Research Lab
Department of Electrical Engineering
Andlinger Center for Energy & Environment
Princeton University, Princeton, NJ, USA

FINAL REPORT

Prepared under contract for UK Power Networks (UKPN)
Project manager:
Mr. Jeremy L. Wright, BEng (Hons) MBA CEng FIET FCMI MIAM
Asset Inspection, Maintenance, and Compliance Manager
Asset Management
UKPN

January 30, 2018

Analysis of Contact-Voltage Losses in Low-Voltage Electricity Distribution Systems of the U.K.

Table of Contents

List of Tables

List of Figures

Executive Summary

Underground contact voltages (CV) commonly result from a break in the insulation of a conductor due to accidental damage during construction work, chemical corrosion, degradation with aging, or other factors. Electricity losses due to such CVs on distribution networks in the UK are estimated in this report to be about 0.59 TWh per year. The unmetered portion of these account for 2.5% of what are traditionally categorized as technical losses from UK distribution networks. CV loss appears to be the single largest avoidable electricity loss on UK networks.

CVs can be detected quickly and efficiently using non-contact mobile methods, as has been demonstrated annually in New York City for more than a decade and in a Central London trial that began in late 2016. In London, a Mobile Asset Assessment Vehicle (MAAV) traversed 425 roadway miles and identified 62 occurrences of CV. Estimating the associated losses using well-established methodologies and extrapolating the loss estimates to the full London Power Network (LPN) license area indicates that some 38 GWh per year of electricity are being lost in the LPN area through CVs. Further extrapolating these findings to distribution networks across the UK gives 0.59 TWh per year of UK-wide losses.

The cost for MAAV-based detection and remediation of CV losses in the UK would be more than offset by the associated benefits, based on the analysis in this report. A key uncertainty is the length of time that a CV would persist in the absence of a MAAV program before it would be detected and repaired. The longer lived a CV would have been, the larger is the benefit of implementing a MAAV program. The cost-benefit ratio is clearly positive even with an assumed CV lifetime of just one year.

1 Contact-voltage faults

The IEEE's *Guide to Understanding, Diagnosing, and Mitigating Stray and Contact Voltage*[1] defines contact voltage as "a voltage resulting from electrical faults that may be present between two conductive surfaces that can be simultaneously contacted by members of the general public or animals. Contact voltage can exist at levels that may be hazardous." CV faults can occur on both overhead lines and underground cables. On overhead lines they are typically readily visible (e.g., electric arcs) and easily and quickly repaired. On the other hand, detecting CV faults on underground cables is more challenging, and repairing them is more involved than repairing faults on overhead lines. Underground cables are found in most populated urban areas of the UK. Contact-voltage faults on underground cables are the focus of this report.

Underground CV commonly results from a break in the insulation of a conductor as a result of accidental damage during construction work, chemical corrosion, degradation with aging, or other external factors. The break allows electricity to leak to ground and/or to energize conducting objects such as manhole covers or lighting columns. Such breaks have minor or even undetectable impacts on a grid's operation. However, they raise public safety concerns and leak energy into the surrounding environment until repaired. The continuous leakage of energy over time can represent substantial cumulative losses.

2 Technical, non-technical, and contact-voltage losses from the UK grid

Losses of all types in electricity networks in the UK totaled about 26 TWh during 2016 (Table 1). This is 7.7% of total electricity supplied from power plants, or equivalent to the annual output of four large (1000 MW) baseload generating units. Losses in the high-voltage transmission system are not insignificant, but these are relatively well understood, closely monitored, and mitigated to the extent practicable. On the other hand, losses in low-voltage distribution systems account for approximately 75% of all losses (assuming "Theft" in Table 1 is associated primarily with the distribution system).

Table 1. UK electricity supply, losses, and final consumption (TWh/year).[2]

	2014	2015	2016
Electricity supplied	342	343	342
Total losses	28.5	27.3	26.3
Transmission	6.51	7.40	7.40
Distribution	21.14	19.07	18.91
Theft	1.00	1.00	1.00
Final consumption	303	303	304

Conventionally, electricity losses in a distribution system are categorized as either technical or non-technical losses.[3] Technical losses are those that occur naturally in system components and cannot be avoided at some level in a properly-operating distribution network, such as core losses in a transformer or resistive losses in cabling. Such losses can be reduced by technology upgrades and new investments – replacing transformers, up-sizing conductors, and other measures – but laws of physics stipulate that technical losses can never be eliminated completely. Non-technical losses comprise electricity that is delivered and consumed, but is not recorded as sold.[4] They are usually caused by actions which are not directly related to the power grid's normal operation, such as theft, improperly functioning meters, or unmetered supplies.

Contact-voltage losses fall outside the conventional definitions of technical and non-technical losses. Unlike non-technical losses, CV losses are not an accounting artifact. They occur due to hardware defects that develop over time, e.g., in cable insulation. The defects (and associated losses) were not present when the hardware was first installed. Unlike technical losses, CV losses, once detected, can be eliminated completely by repair or replacement of the defect. In Table 1, CV losses are part of the losses shown in the row labeled "Distribution". An estimate of the magnitude of the contribution to distribution-system losses from CVs is given in Section 5.

3 Methods for detecting contact voltages

Methods for sensing and locating CV faults can be classified as "contact methods" and "non-contact methods". Contact methods use electrical signals to directly measure electrical impedances, voltage potentials and harmonics on electric cables. Contact methods are accurate and informative – absolute impedance and voltage values can be recorded for detailed investigation of the condition of a cable. In theory, contact methods can accurately find the exact location of, and assess in detail the damage due to, an underground cable fault. In practice, there are limited access points on underground cables, and the accuracy of the impedance or harmonics measurements may be impacted by the noisy electromagnetic environment and sophisticated wire configurations in an urban area, making it difficult to isolate the location of a fault for repair.

Non-contact methods measure the electromagnetic field in nearby environments to infer the conditions of underground cables. Well-insulated underground cables have very high cable-to-ground impedance. If there is a CV fault (e.g., insulation failure), low-impedance paths are established between the cable and the ground, leading to energy loss. A detectable electric field is also established in the surrounding environment near the failure point. One way to sense this electric field is to use capacitive sensing. A capacitor network is placed in the suspected environment to sense voltage differences at two locations near the fault area. A large voltage difference sets up a strong electric field, and a small voltage difference sets up a weak electric field. If there is no CV fault, most of the cable-to-ground voltage difference is blocked by the cable insulation, and the voltage difference in the surrounding environment is small. When a CV fault is present, voltage gradients extend into the surrounding environment and the voltage difference becomes significant enough to be detectable with non-contact methods. The main advantages of non-contact methods are their rapid-detection ability and low operating cost. A so-called Mobile Asset Assessment Vehicle (MAAV) enables rapid detection of CVs and a general estimation of their condition.

Combining MAAV measurements with contact methods enables efficient detection, evaluation, and repair of CVs on underground cables, lighting columns, and other objects.[5] The first step is a non-contact (MAAV) sweep of the electric fields in a wide area. Customized equipment, using sophisticated signal processing algorithms and embedded on a moving vehicle, enables high-speed high-accuracy non-contact electric field detection. A MAAV can rapidly detect electric fields arising from very small voltage differentials at a distance of 10 meters while driving 25 mph. Larger objects or objects at higher voltages can be detected at greater distances. The signature of the electric field is recorded together with time and geographical information as the MAAV traverses a roadway. When an abnormal signal is detected, that location is labeled as a suspect CV location. A field crew then brings contact-method testing equipment to the fault location to perform tests and uses engineering judgement to isolate the location and assess the condition of the fault, after which the fault location and conditions are reported to the utility for repair consideration.

MAAV technology and measurement procedures follow the IEEE guide 1695-2016,[1] and have been used to identify over 130,000 contact-voltages across dozens of utility and municipal distribution networks worldwide.[6] The MAAV approach enables a significant acceleration in the monitoring and repair of underground cables and, thereby, reductions in electricity losses from distribution networks and in potential public health hazards.

4 MAAV-detected contact-voltage loss estimates for Central London

Recognizing the potential benefit of MAAV-based detection and mitigation of CVs, UK Power Networks commissioned a MAAV trial survey of Central London beginning in the 4th quarter of 2016. The survey covered 425 centerline road miles within the London Power Network (LPN) service territory and detected 62 CV occurrences that were energizing 155 objects. The number of CVs at different locations and estimates of associated electricity losses from these are shown in the left two columns in Table 2. The next column shows projections of the number of CVs that would be expected to be found for the entire LPN territory. These projections were developed by linearly scaling the number of CVs detected in Central London by the ratio of total centerline road miles in the LPN (15,100) to the number for Central London (425). From the projected numbers of occurrences, total annual losses for the LPN (last column in Table 2) are estimated assuming on average that losses per CV are as estimated for Central London.

Table 2. Summary results of UKPN's Central London MAAV survey and corresponding estimated electricity losses.

Location of contact-voltage	# of MAAV-detected CVs	Estimated loss per CV (watts)	Projected # of CVs for entire LPN	Estimated losses for entire LPN (MWh/yr)
Customer-side, phase	8	1,380	284	3,436
Low-voltage cable, neutral	10	150	355	467
Low-voltage cable, phase	9	6,144	320	17,210
Lighting column, neutral	24	0.625	853	5
Lighting column, phase	11	4,839	391	16,566
Total	**62**		**2,203**	**37,684**

The loss estimates per CV in Table 2 were developed as follows. Losses from customer-side phase faults are metered losses that were estimated by assuming that they would be no higher than the level that would trip a customer's smallest fuse or circuit breaker (typically 6 amps).* The other categories of contact voltages result in unmetered losses. The neutral cable and neutral

---

* Loss estimate: 6 amps x 230 volts (line voltage) = 1,380 watts.

lighting column losses would be small and very small, respectively, and fixed values were assigned to these (Table 2). The largest losses are for phase-side cable and phase-side lighting column contact voltages.

These latter two categories of losses were estimated by first recognizing that the physical configuration of these types of CVs is analogous to that of earthing conductors widely used in electrical distribution systems. A faulted phase conductor in a buried cable often manifests as an unintentional connection between the phase conductor and its lead or aluminum sheath. At the time of installation, sheaths are continuous and would serve as a path for current if there were such unintentional contact. However, over time, there can be degradation that results in a discontinuous sheath. High fault currents in the sheath can contribute to this degradation, but regardless of the cause, the eventual result is that lengths of shield faulted to phase conductors become isolated and thereby energized at supply voltage level (nominally 230 volts). The intimate contact between such a buried sheath and the soil results in a high impedance fault to earth, much as with an earthing conductor. Similarly, a lighting column becomes energized when the supply phase conductor makes contact with the metal column, which itself is connected by a grounding wire to an earthing rod, effectively resulting in a high impedance fault to earth.

H.B. Dwight's formulas,[7] which were developed in the 1930s based on electromagnetic field analysis and are still a widely-accepted approach for estimating impedances to ground from energized cylinders, were used as a basis for estimating the cable phase and lighting column phase CV losses. For phase-side cable losses, Dwight's formula for the impedance, R, between a buried cylindrical conductor and ground is

$$R = \frac{\rho}{4\pi L}\left(\log_e \frac{16L^2}{as} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} + \cdots\right) \qquad \text{Equation 1}$$

where $\boldsymbol{\rho}$ is the resistivity of the earth (which varies by soil type), $\boldsymbol{L}$ is one-half the length of energized sheath, $\boldsymbol{s}$ is twice the burial depth, and $\boldsymbol{a}$ is the radius to the outside of the sheath. For the phase lighting column, Dwight's formula for impedance from the buried portion of a vertical cylindrical conductor to ground is

$$R = \frac{\rho}{2\pi L}\left(log_e \frac{4L}{a} - 1\right) \qquad \text{Equation 2}$$

where $\boldsymbol{\rho}$ is the earth resistivity, $\boldsymbol{L}$ is the length and $\boldsymbol{a}$ is the radius of the buried portion.

Table 3 gives the values assumed for parameters in Equation 1 for Central London and the resulting loss estimate from a phase cable CV. As part of the Central London MAAV survey work, direct measurements of the current on phase cable faults were made, requiring considerable time and effort. The measurements confirmed that losses estimated using Equation 1 are reasonable.

For estimating phase-side lighting-column CV losses, Equation 2 was applied to calculate the impedance to ground for each of 18 different lighting column designs used in the city of London (Table 4). The average of the 18 values was then used to estimate losses from phase-side CV losses from lighting columns. The soil resistivity was assumed to be as shown in Table 3.

Table 3. Parameter values and resulting impedance to ground and electricity losses for each phase-side cable contact voltage identified in Central London.

Parameter	Value	note
ρ (soil resistivity)	48.6 Ωm	(a)
L (½X energized length)	200 cm	(b)
s (2X buried depth)	25 cm	(c)
a (radius to outer sheath)	1 cm	(c)
R (impedance)	8.61Ω	
Loss (watts)[d]	6,144 W	(d)

(a) This is the average value of the location-specific soil resistivity at each of contact-voltage occurrences detected for cables and lighting columns during the MAAV survey of Central London. Resistivity values were obtained (by purchase) from the British Geological Survey soil database (8).

(b) The length of energized sheath will vary in different occurrences of CVs; 400 cm is representative of energized lengths measured during repair of MAAV-detected contact voltages in the Central London survey.

(c) Based on technical specifications for low-voltage distribution cables in the UK (9).

(d) Calculated as V^2/R, where V is assumed to be 230 volts.

Table 4. Parameter values and resulting impedances to ground from Equation 2 for 18 different lighting column designs used by the city of London (10).[a]

Type of column	*L*, cm (buried depth)	*a*, cm (radius)	*R*, Ω (impedance)
4515[b]	150	15	13.87
8312	120	15	15.90
8315	120	22.5	13.29
8520 **and** 8620	200	28	9.10
8624	220	28	8.61
8535	245	28	8.07
8545	275	28	7.52
TP5-550A-AB-190[b]	120	7.5	20.37
TP12-645C-AB-242	120	15	15.90
TP15-645C-AB-242	200	23	9.86
TP19-866C-AB-292 **and** TP19-1080E-AB-406	200	28	9.10
TP19-1080E-AB-406	200	23	9.86
EP35-1055E-AB-406 **and** E35-845E-AB-292	245	28	8.07
KCH15	120	28	11.88
KCH25	200	28	9.10
Average impedance			**10.93 Ω**
Loss estimate (watts)			**4,839 W**

(a) The values of ***L*** and ***a*** in this table are from (10). Specifically, ***L*** is the length and ***a*** is the radius of the metal cage encased in the concrete footing supporting lighting columns. The cage is constructed of reinforcing bar.

(b) No cage dimensions are shown in (10**)** for column type 4515 and TP5-550A-AB-190. For these, the radius was assumed to be 7.5 cm less than the radius of the footing, since 7.5 cm is the minimum specified concrete cover over the cage, and the length was assumed to be the depth of the footing.

5 Estimated contact-voltage losses across the UK

Based on the results in the previous section, we are able to estimate the magnitude of CV losses across all UK distribution networks. Given the dearth of data on CV occurrences in the UK, this is an order-of-magnitude estimate.

In the previous section, it was projected that 2,203 CV occurrences would be found if MAAV surveying were completed for the entire LPN. The LPN territory has 14,258 miles of low-voltage underground cables and 1,544,655 low-voltage service lines connecting cables to customers.[11] If an average service line is 10 meters long, then there are a total of 23,912 miles of underground cables in the LPN service area.[†] The estimated 2,203 CV occurrences represents an average of 9.2 CV occurrences per 100 miles of cable in the LPN area.

We will assume that 9.2 CV occurrences per 100 miles of cable is representative across the service territories of all 14 distribution network regulatory license areas of the six distribution network organizations (DNO) in the U.K.[‡] There is some evidence to support making this assumption. In particular, the number of energized objects found in the Central London MAAV survey was 36.5 per 100 road-miles. This is surprisingly close to the number of energized objects found per 100 roadway miles in MAAV surveys in 2016 and in 2017 in the Consolidated Edison company's territory in the New York City suburbs of White Plains, Yonkers, New Rochelle, and Mount Vernon (Table 5). Given the distinctly different character of roads and buildings in Central London vs. suburban New York City, the similar number of energized objects detected per mile of MAAV survey suggests that low-voltage underground electrical distribution infrastructures are similar in diverse geographical regions.

Table 5. Results of MAAV surveys for contact voltages in distribution networks in municipalities served by Consolidated Edison of New York.[12]

	2016		2017	
Municipality	**Surveyed road miles**	**Energized objects per 100 mi**	**Surveyed road miles**	**Energized objects per 100 mi**
White Plains	56	62.5	54	42.6
Yonkers	92	47.8	72	30.6
New Rochelle	51	9.8	46	41.3
Mount Vernon	26	7.7	23	39.1
Totals	**225**	**38.2**	**195**	**37.4**

For our estimate of UK-wide losses due to contact voltages, we make a further assumption that the distribution of CV occurrences by type is the same as in the Central London survey (Table 6), and we estimate the losses per CV occurrence for each of the 14 DNO license areas in the UK as follows for each type of occurrence. We take loss estimates for customer-side phase CVs, LV cable neutral CVs, and lighting column neutral CVs to be the same as estimated for Central London (1,380, 150, and 0.625 Watts per CV occurrence, respectively). For phase-side CVs on LV cables and lighting columns, we use the same parameter values for Equations 1 and 2 as used to estimate losses for Central London (see Section 4), except we use soil resistivity values representative of those for each license area. The latter were estimated by visual inspection of the left panel in Figure 1 for major built-up areas in each region on the assumption that most distribution cables are located in the major built up areas. Resistivity values and the resulting estimates of impedances and electrical losses for phase-side cable and phase-side lighting-column CVs are in Table 7.

[†] $23{,}912\ miles = 14{,}258\ miles + \frac{1{,}544{,}655\ service\ lines \cdot 0.01\ km/line}{1.6\ km/mile}$.

[‡] Plastic-sheathed cables, which constitute a small fraction of the total cable miles, are not susceptible to the same contact voltage loss mechanism as the dominant lead- or aluminum-sheathed cables. The 9.2 CVs per 100 miles of cable was derived for the mix of plastic and metal-sheathed cables present in the LPN region, so assuming this mix is similar elsewhere in the UK, the total number of CV occurrences can be estimated by multiplying total cable miles by this factor.

Table 6. Central London MAAV survey results.

Location of contact voltage	# of CVs detected	%
Customer-side, phase	8	13%
Low-voltage cable, neutral	10	16%
Low-voltage cable, phase	9	15%
Lighting column, neutral	24	39%
Lighting column, phase	11	18%
Total	**62**	**100%**

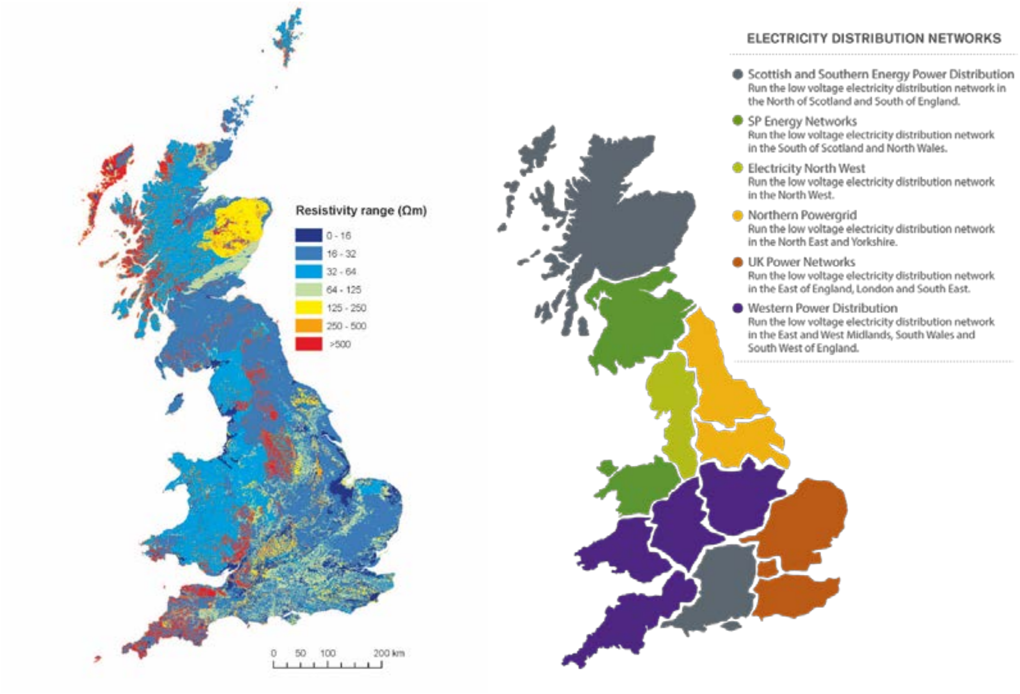

Figure 1. Soil resistivity map of Great Britain (left)[13] and DNO operating territories (right).[14]

Table 8 shows the corresponding weighted-average loss per CV occurrence for all 14 DNO license areas, along with estimates of the total miles of underground LV cable and the estimated number of CVs that would be identified annually if MAAV surveys were undertaken. Also shown are the resulting losses that would be avoided in 12 of the 14 areas if these CVs were repaired. (There were insufficient data to makes estimates for two of the license areas.) Considering the 12 areas for which sufficient data were available, the total electricity losses that would be avoided across the UK by detecting and repairing CVs is estimated to be 591 GWh per year. Of this total, 116 GWh (or about 20%) are metered losses, since they occur due to contact voltages on the customer side of the meter. Considering losses in delivering 591 GWh of electricity to DNOs from power plants, the total lost electricity generation is estimated to be 615 GWh per year (Table 8).

Table 7. DNO-specific loss estimates for phase-side cable and phase-side lighting column contact voltages.

			Cable		Lighting Column	
DNO	**License area**	**Soil Resistivity (Ωm)[a]**	**Impedance (Ω)**	**Loss per CV (Watts)**	**Impedance (Ω)**	**Loss per CV (Watts)**
UKPN	Eastern Power Networks	94.5	16.74	3,160	21.3	2,488
	London Power Networks	48.6	8.61	6,144	10.9	4,839
	South Eastern Power Networks	51.3	9.09	5,821	11.5	4,584
ENW	Electricity North West	48.0	8.50	6,221	10.8	4,899
NP	Northern Powergrid (Northeast)	24.0	4.25	12,442	5.4	9,798
	Northern Powergrid (Yorkshire)	24.0	4.25	12,442	5.4	9,798
WPD	Western Power Distrib. (East Midlands)	24.0	4.25	12,442	5.4	9,798
	Western Power Distrib. (West Midlands)	187.5	33.22	1,593	42.2	1,254
	Western Power Distrib. (South West)	500.0	88.58	597	112.5	470
	Western Power Distrib. (South Wales)	48.0	8.50	6,221	10.8	4,899
SPEN	ScottishPower Energy Networks Distrib.	24.0	4.25	12,442	5.4	9,798
	ScottishPower Energy Networks Manweb	48.0	8.50	6,221	10.8	4,899
SSEPD	Scottish Hydro Electric Power Distrib.	187.5	33.22	1,593	42.2	1,254
	Southern Electric Power Distrib.	48.0	8.50	6,221	10.8	4,899

(a) Except for the London Power Networks (LPN) license area, these have been estimated by visual inspection of the values around major cities in each license area in Figure 1, assuming that most underground low-voltage cables are found in major cities. The value for LPN is an average of specific values from the British Geological survey for locations where contact voltage occurrences were detected during the MAAV survey of Central London.

Table 8. Estimated lengths of underground low-voltage cable miles in each DNO and the corresponding estimated contact-voltage MWh losses that could be avoided annually.

DNO	**License Area**	**Average watts per CV**	**LV cable miles[a]**	**Projected annual CV detections**	**Avoided losses, MWh/yr**
UKPN	Eastern Power Networks	1,110	42,064	3,875	37,430
	London Power Networks	1,961	23,912	2,203	37,684
	South Eastern Power Networks	1,868	28,304	2,607	42,500
ENW	Electricity North West	1,982	32,523	2,996	51,829
NP	Northern Powergrid (Northeast)	3,755	19,739	1,818	59,685
	Northern Powergrid (Yorkshire)	3,755	31,642	2,915	95,678
WPD	Western Power Distrib. (East Midlands)	3,755	37,342	3,440	112,912
	Western Power Distrib. (West Midlands)	664	30,536	2,813	16,170
	Western Power Distrib. (South West)	380	15,937	1,468	4,792
	Western Power Distrib. (South Wales)	1,982	12,127	1,117	19,325
SPEN	ScottishPower Energy Networks Distrib.	3,733	27,021	2,489	81,229
	ScottishPower Energy Networks Manweb	1,982	19,746	1,819	31,467
SSEPD	Scottish Hydro Electric Power Distrib.	664	not avail	not avail	not est.
	Southern Electric Power Distrib.	1,982	not avail	not avail	not est.
	TOTALS	**2,289**	**320,892**	**29,561**	**590,703[b]**
	Total lost generation (assuming 4% loss from generator to DNO receipt)				**615,315**

(a) These are the effective miles of underground cables based on data in [11] and calculated as described in the text. The mileages are for 2015/2016, except for UKPN, for which 2016/2017 data were available.

(b) Of this loss estimate, approximately 80% is unmetered (20% is on the customer side of the meter).

6 Contact-voltage loss estimate in perspective

The estimated unmetered CV losses on UK distribution networks (474 GWh/year) represent 2.5% of what are traditionally called technical losses on distribution systems across the UK. This makes contact voltage losses the single largest avoidable loss in the distribution system. Other types of technical-loss reductions in distribution networks include replacing transformer cores, upsizing cable conductors, and others. In 2015, it was projected that the combined total of concretely identified loss-reduction measures and potential loss-reduction measures (excluding CV repairs) across DNOs for the period 2015/16 – 2022/23 was 204 GWh/year on average (Table 9), or less than half of our estimate of potential unmetered CV losses that could be avoided and only about one-third of unmetered plus metered CV losses.

Table 9. Estimated loss reduction potential across UK DNOs via implementation of various measures [3].

	MWh/year
Concrete measures[a]	
Replace old transformers	35,179
Install low-loss transformers	10,670
Oversized conductors	28,962
Optimizing conductors	7,881
Voltage control	3,424
Subtotal	86,116
Potential measures (unspecified)[b]	
Technical potential	118,303
Total	**204,419**

(a) These are the average of projected annual savings for each measure for 2015/16 – 2022/23. According to [3], the data supporting the projections are from the individual losses strategies as published by each DNO.

(b) These are measures in different stages of investigation by DNOs. The value here is the average of a high and low estimate. According to [3], the measures include changing conductor material (e.g., aluminum to copper), reducing winding resistance of transformers, replacing oil as the dielectric material in transformers with epoxy resin, and a variety of other measures.

7 Cost-benefit analysis of MAAV-based CV detection and repair

Financial costs to identify and eliminate contact voltages via MAAV surveys can be weighed against the resulting benefits. We adopt the cost-benefit accounting framework promulgated by the UK's Office of Gas and Electricity Markets (OFGEM) for use by DNOs in assessing costs and benefits of proposed implementation of a loss-reduction measure.[15] In this framework, the costs of implementing a measure are compared against the costs that would have been incurred if the measure had not been implemented, i.e., they are compared against the costs in a "business-as-usual" (BAU) scenario.

7.1 The business-as-usual (BAU) scenario

There are relatively little data on the rates at which contact voltages come into existence on distribution networks, which introduces some uncertainty in defining a BAU scenario for the cost-benefit analysis. The best available public data on contact voltages are those reported by the Consolidated Edison Company of New York, Inc ("ConEd").[16] New York state standards require ConEd to conduct annual CV testing for all streetlights and for all underground electric facilities that are publicly accessible, including, but not limited to manholes, service boxes and transformer vaults. As a result, for nearly a decade, ConEd has been conducting annual MAAV surveys of its entire service territory and remediating all energized objects discovered in the surveys. Table 10 reports the annual rate of detection and repair. The number detected annually is significant, and it varies from year to year but with no clear trend. Considering that the ConEd MAAV surveys cover the same geographical area each year, the data suggest that a reasonable model for a BAU scenario is that the number of new contact voltages arising on a network each year is approximately constant. This is the BAU scenario we adopt for the cost-benefit analysis in this report.

Table 10. Number of objects energized (to one volt or higher) by contact voltages identified via MAAV surveys each year by Consolidated Edison of New York, Inc. across its full service territory.

Year	# of energized objects found and repaired
2009	11,041
2010	9,553
2011	8,560
2012	6,871
2013	7,451
2014	8,920
2015	7,175
2016	9,233
2017	data not yet available
Source: (16)	

Since losses from an unrepaired CV in the BAU scenario would continue until the CV is repaired, an additional assumption must be made about the length of time that a CV would have persisted in the BAU scenario before it would have been repaired. The longer that a CV would have persisted, the greater are the avoided electricity losses resulting from a MAAV-based detection/repair program. Unfortunately, there are very little data available for informing what value to assume for the average "lifetime" of a CV in the BAU scenario. Consequently, we have chosen to examine the impact on the cost-benefit analysis of assuming lifetimes ranging from 1 to 3 years. We assume in the BAU scenario that after a given CV has reached the assumed lifetime it would be repaired.

To illustrate how the assumed BAU CV lifetime enters the cost-benefit analysis, Figure 2 depicts the reduced electricity losses from a MAAV-based program relative to BAU for an assumed BAU CV lifetime of 3 years. As suggested by the ConEd data in Table 10, a constant number of new CVs appear each year in the BAU scenario. For a CV lifetime of 3 years, each new cohort of CVs persists for 3 years before being repaired. Meanwhile, in the MAAV scenario, CVs are repaired in the same year they appear. Thus, at steady state (years 3 and beyond in Figure 2), there are three cohorts of unrepaired CVs in the BAU scenario for each repaired cohort of CVs in the MAAV scenario, i.e., electricity losses avoided by the MAAV program in a given year are 3 times the amount of losses that would occur from the number of CVs repaired in the MAAV program. Analogously, for BAU CV lifetimes of one or two years, the avoided electricity losses resulting from the MAAV program are, respectively, one or two times the amount of losses that would occur from the number of CVs repaired in the MAAV program.

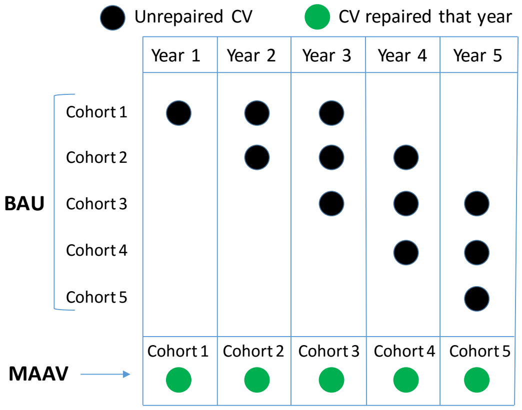

Figure 2. Illustration of the number of unrepaired CVs that would exist in the BAU scenario for each CV that would have been detected and repaired had a MAAV program been implemented. This illustration assumes that each CV in the BAU scenario persists for three years before it is repaired.

7.2 Additional assumptions for the cost-benefit analysis

Costs included for our analysis are the annual cost for MAAV services, including detection and repair of CVs, and the annual greenhouse gas emissions (GHG) associated with operating the MAAV truck. Avoided costs include those that a DNO would have incurred to repair CVs in the BAU scenario, as well as costs it would have incurred in responding to fuse trips due to unrepaired CVs. Additionally, we include the following societal avoided costs in the MAAV scenario: ***1)*** electricity generation losses, ***2)*** GHG emissions associated with the avoided electricity losses, ***3)*** local air pollutant emissions associated with the avoided electricity losses, ***4)*** a reduced number of customer interruptions caused by fuse trips resulting from unrepaired CVs, ***5)*** customer electricity-supply minutes lost due to fuse trips, ***6)*** reduced risk of fatalities from electrical shock caused by a CV, and ***7)*** reduced risk of serious injury from a shock caused by a CV.[§]

Table 11, Table 12, and Table 13 list key quantitative input assumptions for the cost-benefit analysis (CBA), with details provided in the table notes. In Table 11, the upper section refers to the BAU scenario. The lower section shows parameters for a MAAV-based survey/repair program. The analysis here is for a single MAAV unit operating for an 8-year program period.

[§] These societal avoided costs are the same as those included in OFGEM's cost-benefit analysis framework,[15] except the latter does not explicitly include item ***3)***.

Table 11. Input assumptions for cost-benefit analysis.

Business-as-usual, i.e., with no MAAV program	
Average lost electricity generation[a]	14,090 MWh/year
Number of fuse trips per CV[b]	3 per year
Customers interrupted per fuse operation[c]	10
Customer minutes lost per fuse operation[c]	60
Lifetime that a CV persists before it is repaired[d]	range: 1 – 3 years
With MAAV survey/repair program	
Number of MAAV-detected phase-side cable CV[e]	115 per truck-year
Reduced risk of fatality due to shock from CV[f]	10%
Reduced risk of major injury due to shock from CV[f]	15%
CO_2 emissions from one MAAV truck	6 tCO_{2e}/year

(a) This is the amount of electricity estimated to be lost due to contact voltages equivalent to those that would be identified by a single MAAV truck surveying continuously for one year. The estimate was derived as follows. A MAAV survey of the full LPN license area would identify contact voltages that collectively result in 37,684 MWh per year of losses (Table 2). If MAAV trucks were to operate 24 hours per day for a year (excluding bank holidays), it is estimated that 2.786 trucks would be required to complete a full survey of the LPN. On this basis, the electricity losses associated with CVs detected by a single truck would be 37,684/2.786 = 13,526 MWh/year. Guidance from OFGEM for cost-benefit analysis of proposed improvements to distribution networks [15] indicates that 4% losses in moving the electricity from the point of generation to the point of loss in the distribution system should be included: 13,526 / (1 – 0.04) = 14,090 MWh/year.

(b) UKPN estimate. Unrepaired CVs can cause fuses on the network to trip, necessitating a reset. Under BAU operation it is estimated that a fuse trip occurs on average 3 times per year for each contact voltage.

(c) UKPN estimate.

(d) See discussion in text.

(e) Phase cable contact voltage faults, if not avoided by a MAAV program, would have resulted in BAU costs associated with fuse trips, customer interruptions, customer minutes lost, and eventually detection and repair. A total of 320 occurrences of phase cable CVs are projected for a one-year survey covering the full LPN area (Table 2). As indicated in table note (a) above, an estimated 2.79 MAAV trucks would be required to accomplish a full LPN survey in one year. Thus, the expectation is that one MAAV unit would detect 320/2.79 = 115 phase cable contact voltages.

(f) The risks of fatalities and of major injuries are assumed to be reduced by 10% and 15% when a MAAV program is in place.

Table 12. Valuations of costs and benefits associated with MAAV detection and repair of contact voltages.[a]

Costs incurred with MAAV program	
CV detection and repair for an 8-year program[b]	£2.39 million per year
GHG emissions from operating MAAV	see Table 13 for emissions costs
Costs avoided	
Repair of contact voltages[b]	£ 0.46 million per year
Responses to fuse operations[b]	£ 250 per fuse operation
Societal avoided costs	
Electricity generation[c]	£ 48.42 per MWh
GHG emissions from electricity generation	see Table 13 for emissions costs
Air pollution from electricity generation	see Table 13 for emissions costs
Customer interruptions (CI)[c]	£ 15.44 per CI
Customer-minutes lost (CML)[c]	£ 0.38 per CML
Fatality due to CV shock[d]	£ 1.79 million per fatality
Risk of a major injury[d]	£ 27,488 per major injury
Financial parameter assumptions	
Weighted-average cost of capital (real)	4.08%/year
DNO asset capitalization rate[c]	85%
Capital depreciation[c]	Straight-line, 45 years

(a) All monetary values are given in 2013 £.

(b) UKPN estimate.

(c) OFGEM guidance for cost-benefit analysis [15].

(d) Source: OFGEM guidance [15], based on Health and Safety Executive guidelines [17]. The corresponding cost avoided by the MAAV program is this value multiplied by the assumed percentage risk reduction shown in Table 11.

Table 13. Greenhouse gas (GHG) emission trading prices, air pollution damage costs, and grid electricity GHG emissions recommended by the UK government (BEIS) and by OFGEM for use in appraisals. The analysis in this report uses the OFGEM values where available.

	GHG Trading Prices (2012/2013 £/tCO_{2e})				Air pollution damages, generation based (£/MWh)	Grid-average GHG emissions, generation-based (tCO_{2e}/MWh)	
	BEIS[a,b]			OFGEM[c]	BEIS[a,b]	BEIS[a]	OFGEM[c]
	Low	**Central**	**High**				
2017	0.0	4.1	4.1	7.67	0.157	0.265	0.488
2018	0.0	4.1	4.4	8.16	0.160	0.235	0.474
2019	0.0	4.2	6.9	8.68	0.163	0.224	0.459
2020	0.0	4.4	8.8	9.24	0.166	0.198	0.445
2021	3.7	11.4	19.1	16.49	0.170	0.194	0.430
2022	7.4	18.4	29.4	23.74	0.173	0.161	0.416
2023	11.2	25.4	39.7	30.98	0.177	0.171	0.401
2024	14.9	32.4	50.0	38.23	0.180	0.184	0.387
2025	18.6	39.4	60.3	45.48	0.184	0.174	0.372
2026	22.3	46.5	70.6	52.73	0.187	0.153	0.358
2027	26.1	53.5	80.8	59.98	0.191	0.143	0.343
2028	29.8	60.5	91.1	67.23	0.195	0.118	0.329
2029	33.5	67.5	101.4	74.48	0.199	0.103	0.314
2030	37.2	74.5	111.7	81.73	0.203	0.107	0.300

(a) From [18].
(b) Originally given in 2016 £, converted to 2012/2013 £ using UK GDP deflators [19].
(c) From **[**15**].**

7.3 Results

Figure 3 shows discounted annual costs and benefits for an 8-year MAAV-based CV detection and repair program starting in 2018, assuming that without the program CVs would have persisted for 1 year before being repaired. By far the largest benefit each year is avoided electricity losses. Reduced risks of fatalities are a distant second largest benefit. The other benefits are each relatively small individually, but the avoided CO_2 emissions grows to become the second largest benefit in the 7th and 8th years of the program.

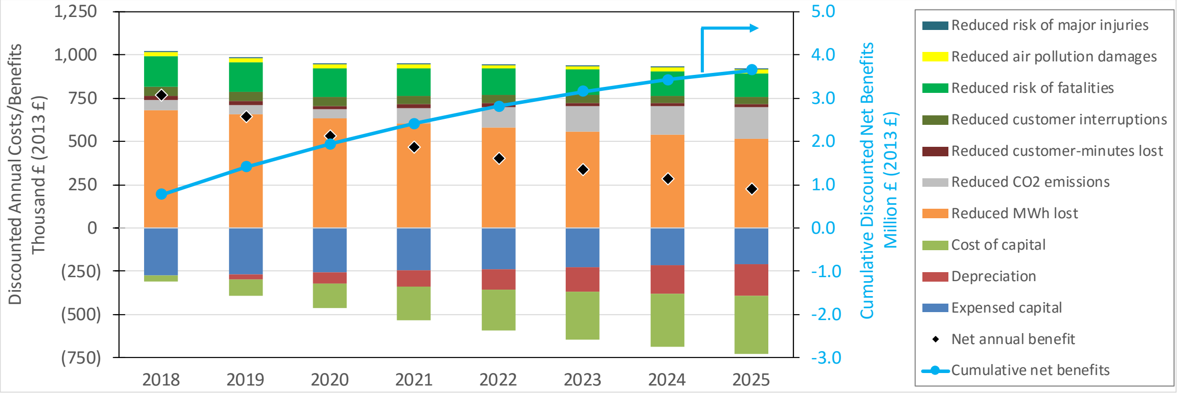

Figure 3. Discounted annual costs and benefits (left axis) and cumulative discounted net benefits (right axis) for an 8-year MAAV-based CV detection and repair program, assuming CVs persist for 1 year in the BAU scenario.

In the OFGEM cost-benefit analysis framework used here, the value of a loss-reduction investment is judged by the cumulative discounted net benefit resulting from its implementation.

The cumulative discounted net benefit for the MAAV program grows from £0.77 million in the first year to £3.65 million at the end of the program (year 8), as shown in Figure 3. If the CV lifetime assumed for the BAU scenario were 2 years instead of one, the cumulative discounted net benefit in year 8 grows to £10.6 million, and if a BAU CV lifetime of 3 years were assumed, the net benefit grows to £17.5 million (Figure 4).

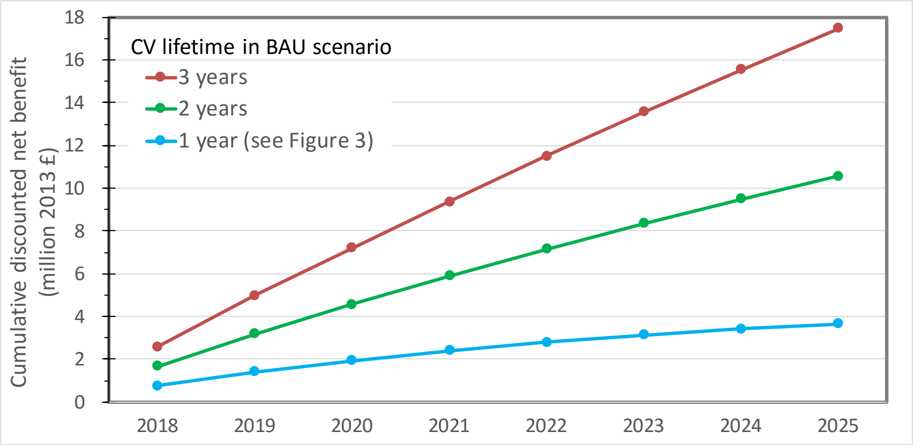

Figure 4. Discounted annual costs and benefits for an 8-year MAAV-based CV detection and repair program with different assuming CV lifetimes in the BAU scenario.

8 Conclusions and some reflections

Based on the analysis in this report, contact-voltage losses are one of the single largest avoidable loss of electricity from distribution networks in the UK. Our order-of-magnitude estimate is that they account for about 2.5% of unmetered distribution system losses in the category traditionally defined as technical losses. By comparison, upgrades to transformers, upsizing of conductors, and other measures might collectively reduce technical losses by only about 1%. Moreover, if such losses are reduced by over-sizing components, then the upgraded assets will be under-utilized until load catches up, at which point the losses return. Given that considerable capital investment may be required for such upgrades, and may include retiring existing equipment before the end of its useful life, are the ratio of benefits to costs for such measures as positive as our analysis suggests they are for eliminating CV losses? Detailed cost-benefit comparisons, which are beyond the scope of this work, are needed to answer this question.

Finally, it is of interest to consider how the future evolution of the electricity grid might impact the frequency of contact-voltage losses. For example, what might be the impact in a future low-carbon grid that includes massive distributed renewable generation? It is difficult to be more than speculative in answering such questions. However, it is safe to say that where existing distribution cables are no longer needed and are taken out of service, contact-voltage losses would diminish correspondingly. On the other hand, unlike some technical losses, such as transformer losses, contact-voltage losses are independent of power flow: they depend only on the line voltage and the impedance to ground. Thus, to the extent that line power flows diminish, e.g., due to greater distributed self-generation and associated self-consumption, technical losses other than CV losses will diminish, and, *ceteris paribus*, contact-voltage losses will become a larger fraction of total losses.

9 References

1. Transmission and Distribution Committee, "IEEE Guide to Understanding, Diagnosing, and Mitigating Stray and Contact Voltage," IEEE Standard 1695-2016, Power and Energy Society of the Institute of Electrical and Electronics Engineers, New York, NY, 2016.
2. UK Department for Business, Energy and Industrial Strategy, Digest of UK Energy Statistics (DUKES): electricity," 27 July 2017.
3. UK Office of Gas and Electricity Markets, "Energy Efficiency Directive: An assessment of the energy efficiency potential of Great Britain's gas and electricity infrastructure," OFGEM, 16 June 2015.
4. UK Office of Gas and Electricity Markets, "Electricity distribution losses: a consultation document," OFGEM, January 2003.
5. Wright, J.L., "Surveying for Electrical Losses," *Electric Energy T&D Magazine*, Jan/Feb 2016 issue.
6. Wright, J.L., "Losses on the low voltage underground cable network due to contact voltage," presentation at UK Power Networks Losses Stakeholder Event, Imperial College, Kensington, London, 6 July 2017.
7. Dwight, H.B., "Calculation of Resistances to Ground," *Electrical Engineering*, 55(12): 1319 – 1328, Dec. 1936.
8. Entwisle, D.C., White, J.C., Busby, J.P., Lawley, R.S., and Cooke, I.L., "Electrical Resistivity Model of Great Britain: User Guide," *British Geological Survey Open Report*, OR/14/030, 2014.
9. British Standards Institution, "Specification for Impregnated paper-insulated lead or lead alloy sheathed electric cables of rated voltages up to and including 33 000 V," BS 6480:1988, Incorporating Amendments Nos. 1 and 2 and Corrigendum No. 1), 21 Feburary, 2003.
10. City of London, "Supplemental Standards for Traffic Signal and Street Lighting," STS 5.02, Nov. 3, 2017.
11. DNO-Shared Asset Database, provided by UKPN to the authors.
12. Consolidated Edison Co. of New York, Inc., "Report on Mobile Testing for Contact Voltage Performed Outside of New York City," 10-E-0271, 24 July 2017.
13. CP17/050 British Geological Survey © NERC [2017]. Permission to reprint this map provided to Eric Larson by the Natural Environmental Research Council as represented by the British Geological Society, 14 Aug 2017.
14. Source: UK Office of Gas and Electricity Markets (OFGEM) website.
15. OFGEM's spreadsheet template for cost-benefit analysis (filename: Template CBA RIIO ED1 v4.xls) provided to the authors by UKPN.
16. Consolidated Edison Co. of New York, Inc., "Contact Voltage Test and Facility Inspection Annual Report," filed each February pursuant to the requirements of the NY State Public Service Commission's Electric Safety Standards issued in Case 04-M-0159 (Proceeding on the Motion of the Commission to Examine the Safety of Electric Transmission and Distribution Systems). All published reports are available here.
17. Health and Safety Executive, "Cost-Benefit Analysis (CBA) Checklist," website, Government of the UK, accessed 13 Oct 2017.
18. Department for Business, Energy and Industrial Strategy,"Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal," UK Government, 15 March 2017 (URL).
19. HM Treasury, GDP deflators at market prices, and money GDP September 2017 (Quarterly National Accounts, September 2017), 2 October 2017. (accessed 31 October 2017)