# Strategies for reducing losses in distribution networks

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# Content

# Executive Summary

The key objectives of the modelling and analysis carried out by Imperial College, presented and analysed in this report, are:

- Provide new insights and understanding of network losses in UK Power Networks' distribution networks by quantifying losses across different network segments. This covers each of their three licence areas and considers the impact and significance of different losses drivers relative to each area;
- Assess the effectiveness of alternative loss management strategies through the consideration of network reconfiguration, power factor compensation, phase unbalance management and power harmonic reduction;
- Investigate the opportunities for the application of novel smart grid technologies, already deployed by UK Power Networks' Innovation team, to manage network losses;
- Identify areas with high losses and determine the optimal approach to manage losses within these areas. Quantify the potential losses reduction in these areas and use these findings to inform UK Power Networks Losses Management Strategy;
- Investigate efficient loss reduction investment strategies including the application of low-loss transformers, investment in high-capacity cables and overhead lines including service cables, converting single-phase and Scott connected networks to three-phase supplies and the impact of (removing) tapering;
- Support dissemination and communication of learnings across DNO community.

***Modelling Framework:***

Using the established Load Related Expenditure (LRE) model as a foundation, a new modelling tool - Loss Operation & Investment Model (LOIM), has been developed and applied throughout this project. The extent of the model covers all three licence areas served by UK Power Networks from low voltage networks to grid supply points and has been used to calculate losses within these areas. This is in stark contrast to the previous analysis of network losses that has traditionally been based on the application of representative distribution networks[1]. The LOIM has been used to generate Losses Heat Maps for each of UK Power Networks' areas in order to identify the regions in which network losses are most significant. The effectiveness of various network losses-reduction techniques in different UK Power Networks areas were analysed in detail to provide core insights regarding the business cases for alternative losses mitigation strategies and losses-driven network infrastructure investment.

**Quantification of network losses**

The analysis carried out highlighted that more than 75% of network losses are associated with LV networks, HV networks and distribution transformers. Overall:

- 36-47% of the total losses are in LV networks
- 9-13% of losses are associated with distribution transformer load related losses
- 7-10% of losses are associated with distribution transformer no-load losses
- 17-27% are in HV networks

[1] Imperial College London and Sohn Associates, *Management of electricity distribution network losses*, supported by UKPN and WPD, 2014

- 17-24% of total losses are in primary and grid transformers, and EHV and 132 kV networks.

Understanding the contribution of different network sections to the total losses will be important when identifying loss management strategies, assessing corresponding cost effectiveness and determining the potential impact of those strategies.

**Distribution of losses across network segments**

Asset utilisation and circuit lengths are major losses drivers and hence their impacts have been investigated and analysed across each region. UK Power Networks operate a wide range of network types. These range from rural areas, such as parts of Norfolk and Suffolk, to very densely populated urban areas like London. The corresponding peak demand density varies from a very low 0.05 $MW/km^2$, to a relatively high density of 137 $MW/km^2$. In this context, average utilisations of distribution transformers of 51% and 38% are observed in LPN and EPN areas respectively.

Furthermore, the proportion of transformers which have a utilisation factor in excess of 70% in LPN is 20%, while in EPN this figure is only 4%.

Detailed power flow modelling revealed that HV feeders in LPN deliver an average of 50% more energy than feeders in EPN, while circuits in LPN are typically about 60% shorter than in the EPN region. In this context, the analysis demonstrated that losses in LPN are primarily driven by high network utilisation, while in EPN, losses are driven by long feeder lengths. Overall, the LV network losses are comparable in both areas despite LPN LV networks having significantly shorter lengths but higher loading. Conversely, losses in the HV networks are greater in the EPN region.

The analysis demonstrated that the magnitudes of losses vary significantly across each network type. Modelling quantified losses for more than 4,000 HV feeders, demonstrating a relatively small number of HV feeders are characterised with high losses. About 70% of the total losses are in 20% of the feeders. This clearly demonstrates that loss reduction initiatives in HV networks should target a relatively small proportion of the feeders characterised by these high losses. Undertaking a targeted approach will maximise the cost efficiency of this activity. An unequal distribution of losses was noted in the LV network with more than 50% of losses noted to occur in only 20% of LV feeders.

Based on advanced neural networks methodology, UK Power Networks' HV feeders and LV networks were classified into 22 clusters. These clusters were determined according to the number of customers and their load characteristics, network length, rating, type and construction. Average parameters for each cluster were quantified and corresponding representative networks created. These included a range of rural and urban networks, and the related loss performance for each was assessed.

As a significant amount of losses are associated with a small number of very specific feeders, it should be noted that use of generic feeders with average parameters may not provide appropriate evidence to inform the development of effective losses reduction strategies.

**Identification of potential operational strategies for loss reduction**

A number of key losses drivers were identified and analysed. Learning from this analysis can be used to inform the development of future losses reduction strategies. These include changes in network operational topology, improvement of power factor, changes in load profile, controlling phase imbalance and harmonic distortion.

Key results of conducted case studies are as follows:

- Analysis demonstrated that Normally Open Point (NOP) reconfiguration could reduce HV feeder losses by up to 15% in specific areas. The economic case for this operational strategy, as a result, appears to be strong.
- For the three UK Power Networks licence areas feeders are ranked by the possible reduction in losses driven by power factor improvement. The potential for loss reduction is assessed assuming power factor improvement from 0.85 to 0.95. This would lead to reduction in losses on each feeder between 11% and 14%. It is interesting that the modelling demonstrated that improving power factor in only one third of HV feeders could achieve 90% of potential losses reduction. Hence, the list of 30 highest ranked HV feeders in each licence area is created and measurements of the actual power factor in future trials are proposed to be carried out.
- It was noted that phase imbalance increases losses non-linearly. For example, phase imbalance ranging from 10% to 30% would increase losses by 5% to 45% respectively. As a consequence, we identified a list of 30 LV networks that would deliver the highest benefits for imbalance improvement, based on the networks' electrical characteristics.
- Implementing voltage management across UK Power Networks' three licence areas could potentially reduce losses by around 5%. Further investigation is required to understand the voltage dependency of customer loads. Measurements are recommended to enhance the understanding of voltage dependency in real time. This information will aid the formation of future loss mitigation strategies. Performing actual measurements of voltage dependency of demand in different segments of the network should provide key information related to the potential development of corresponding loss mitigation strategies.
- Harmonic distortion is limited though network design standards, which ensure that the impact of harmonic currents on networks are limted. The impact of voltage harmonics on transformer no-load losses is linearly dependant on the total harmonic distortion (THD), and hence, the impact on losses in this domain is more significant. Eco design transformers' iron losses are lower than previous transofmer specifications. The net effect of this should mean that the impact of harmonic distortion on no-load losses will decrease over time.

**Application of smart-grid technologies for reduction of network losses**

- Modelling demonstrated that the use of UK Power Networks' Quadrature Booster, beyond the network constraint management utilised by their Flexible Plug and Play (FPP) project[2], could deliver savings in the local network losses from about 11% in the case of high demand and high distributed generation (DG) growth, up to 25% for low demand and low DG growth.
- Furthermore, modelling demonstrated that optimally controlling the power factor of distributed generators in the FPP project area could potentially reduce 33kV network losses by 13%.
- Smarter Network Storage (SNS)[3] installed in Leighton Buzzard to manage peak demand and postpone network reinforcement (in addition to delivering system balancing services), could potentially reduce losses in supplying circuits by about 15%.

[2] http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Plug-and-Play-(FPP)/
[3] http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Smarter-Network-Storage-(SNS)/

- Modelling demonstrated that Soft Open Points (SOPs)[4], installed for the management of constraints in LV feeders, could potentially reduce losses in the corresponding LV network and distribution transformers by about 10%-15%.
- Potentially further reduction in losses could be achieved by optimizing NOP positions in real time to take into account changes in demand and generation.
- The former Department of Energy and Climate Change (DECC) indicated that smart meters, combined with home display units, could reduce energy consumption by 2.8%[5]. Analysis showed that correspondingly, distribution network losses would reduce by 5.5% due to the decrease in consumption.
- Furthemore, analysis demonstrated that demand side response, which could potentially shift 2.5% load from peak to off-peak period, would lead to a reduction of losses by about 3%.

**Identification of efficient loss reduction investment strategies**

- UK Power Networks could save 17GWh per annum by replacing all Health Index 4 and 5 distribution transformers with Ecodesign units. Given the current rate of replacement, savings could reach up to 3.2 GWh per year.
- Loss reduction benefits alone are not sufficient to justify the upgrade of existing underground cables. Howerver, when thermal constaints drive network reinforcement , installing cables of higher capacity would significantly reduce losses. In this context, analysis carried out to determine the benefits in loss reduction by adopting a minimum feeder cross-section area of 185 mm². This would reduce LPN HV feeder losses by 10%. The corresponding values for EPN and SPN are 40% and 32% respectively. Removing tapering could potentially decrease losses by up to 25%. For LV networks, the benefits of applying larger cables would be very significant, ranging from 52% to 63%, depending on the area.
- Using 30-minute samples tends to understate network losses, particularly in service cables that supply one customer only. To inform this process, 5,000 five-second samples from the Low Carbon London (LCL)[6] project were used comparatively. This modelling demonstrated that applying higher sampling rates increases calculated losses by a factor of 1.9 compared with the losses estimated using half-hourly profiles (the range is from 1.2 to 5.8). This further reinforces the case for significantly increasing the standard capacity of service cables.
- If single-phase HV spurs are converted to three phase, losses could potentially be reduced by up to 80% in the corresponding network.

**Benefits of loss reduction strategies**

Based on the analysis carried out, the capitalised value of the benefits associated with alternative loss reduction strategies are summarised in Table 1 below. The annual capitalised benefit is calculated by applying a discount rate of 3.5%.

[4] http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Urban-Networks-Low-Voltage/
[5] https://publications.parliament.uk/pa/cm201617/cmselect/cmsctech/161/161.pdf
[6] http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Low-Carbon-London-(LCL)/

Table 1 - Capitalised value of the benefits associated with alternative loss reduction strategies

| Strategy | Capitalised value | Comment |
|---|---|---|
| **NOP optimisation** | £5.4-8.9m | LPN area |
| **HV smart switches** | £2.6-4.3m | LPN area |
| **Multiple power factor correction per HV feeder** | SPN £48-80k<br>EPN £56-92k<br>LPN £53-88k | Minimum for 30 'best' HV feeders per each licence area if power factor is reduced from 0.85 to 0.95; the power factor is not yet measured and hence potential value might be lower of higher |
| **Single point power factor compensation per HV feeder** | SPN £25-41k<br>EPN £30-49k<br>LPN £28-46k | Minimum for 30 'best' feeders per each licence area if single point compensation is installed. Potential value depends on actual power factor |
| **Voltage control** | LV £1.5-2.4k per site<br>HV £9.2-15.2k per feeder | Maximum expected value for voltage dependent loads (constant power and constant impedance); for mixes different types of loads, i.e. constant power, constant current and constant impedance based loads, the benefits of voltage control are marginal. |
| **LV load balancing** | £0.9-13.6k per site | LPN LV network |
| **LV harmonics** | £200-300 per site | |
| **Primary transformer de-energisation during low load conditions** | Negligible | For typical transformer load and no-load losses, the benefit is negligible; in the event of high no-load losses relative to load losses[7], the potential benefit could be £49-81k per substation |
| **Eco-design transformers** | £4-7.4k per transformer | Average savings per transformer (392 transformers considered) |
| **Amorphous transformers** | £0.9-1.4k per PMT | Average savings per PMT transformer (15 pole mounted transformers (PMTs) considered) |
| **Conductors rationalisation** | LPN LV £63-104m<br>LPN HV £1.1-1.8m<br>EPN LV £114-188m<br>EPN HV £24-39m<br>SPN LV £87-144m<br>SPN HV £15-25m | All conductors lower than Al 185 mm² are replaced with Al 185 mm² conductors.<br>LPN HV network already uses relatively higher conductor sizes and hence benefit is relatively lower than in EPN and SPN. |

[7] High no-load losses imply older transformers, which based on life expectancy, could reduce the indicative value of the capitalised benefits as these might be replaced, based on condition, before the full benefits are achieved.

| Strategy | Capitalised value | Comment |
|---|---|---|
| **SPN HV voltage rationalisation** | Min 11 kV £7.3-12m<br>Min 20 kV £59-97m | - SPN HV voltages 2.2, 3.3 and 6.6 kV are upgraded to 11 kV, 2,300 km of conductors<br>- All HV voltages are upgraded to 20 kV, 17,700 km of conductors<br>- Impact of transformers is not taken into account |
| **LPN EHV voltage rationalisation** | £12-19m | LPN 33 kV network is upgraded to 132 kV, 6,100 km of conductors; Impact of transformers is not taken into account |
| **Smart distribution transformer8** | £7.4-12.3k per secondary site | Minimum benefit per site [considering EPN 30 'best' sites for voltage control on LV network (4% loss reduction), HV network (5% loss reduction), power factor improvement (8% loss reduction) and phase imbalance reduction (5% loss reduction)] |
| **Scott connected transformers** | £10.4-17.3k per site | SPN LV networks supplied from 307 Scott connected transformers |
| **Impact on transmission system** | Average savings on National Grid's networks of up to 5.5% could be achieved | Savings are due to reduced active power on UK Power Networks regions. Control of reactive power could potentially generate additional savings. |

[8] Typically distribution transformers are equpted by off-load tap changers to adjust for a seasonal variation in expected voltage range. Smart distribution transformers could control voltage during operatioin in order to, for example, reduce losses.

# 1 Quantification of network losses

Comprehensive case studies have been carried out to quantify the impact that various losses-drivers have on overall network losses. These drivers were ranked in terms of their corresponding impact. On the basis of the Load Related Expenditure (LRE) model concept a new modelling tool, Loss Operation & Investment Model (LOIM), has been developed and applied for the first time, to the detailed quantification of losses in distribution networks within the licence areas of UK Power Networks. Furthermore, LOIM has been applied to generate Losses Heat Maps for UK Power Network's EPN and LPN network licence areas. The effectiveness of various loss-reduction techniques in different areas were analysed in detail. The LOIM tool was also utilised to assess losses performance in different network types and configurations in order to provide core evidence for creating representative networks based on the parameters that drive their corresponding losses performance.

## 1.1 Loss Operation & Investment Model

The LOIM was developed to quantify losses in UK Power Networks' licence areas. This model was used to assess the impact of different demand and network parameters that are known to influence losses (e.g. power factor, network phase imbalance, harmonics etc.), and assess the loss-improvement impact of alternative loss-mitigation techniques (e.g. optimisation of normally-open points) and investment strategies (size of cables, low loss technologies). The main components of the LOIM model are presented in the flow diagram depicted in Figure 1.1.

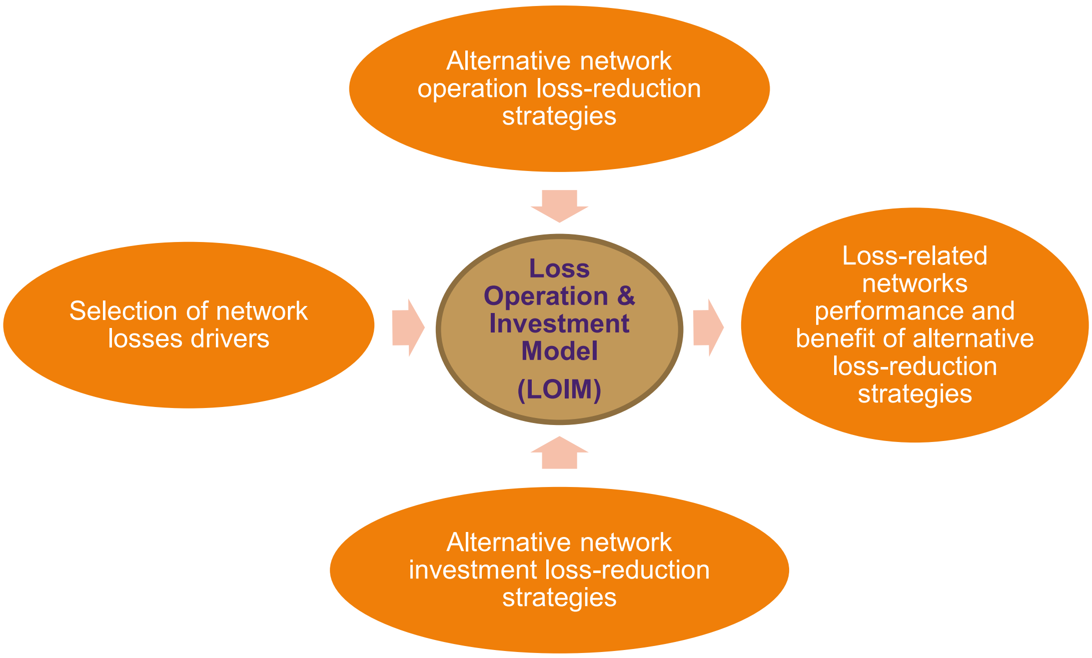


Figure 1.1. Loss operation and investment model

The LOIM contains a detailed network model of the entire UK Power Networks area, in contrast to previous modelling carried that was based on representative distribution networks only.

The magnitude of losses in a given network depends on load and voltage profiles, demand power factors, demand phase imbalance, and harmonics. In this project, network losses are quantified and presented using detailed spatial resolutions in the form of loss heat maps, described in the following section.

## 1.2 Losses Heat Maps

Losses heat maps were developed to identify regions of each of UK Power Networks' licence areas in which magnitude of losses are highest. Relevant data is obtained from the studies carried out using the LOIM tool. Each licence area is split into squares of 500 x 500 metres. Every Distribution Transformer (DT) in the licence area is associated with a particular square. It should be noted that more than one DT could be associated with a particular square in which case losses are the sum of losses associated with each DT. The magnitude of annual losses is quantified for each 500 x 500 metre square across UK Power Networks' licence areas. The losses heat maps generated are shown in Figure 1.2, Figure 1.3 and Figure 1.4.

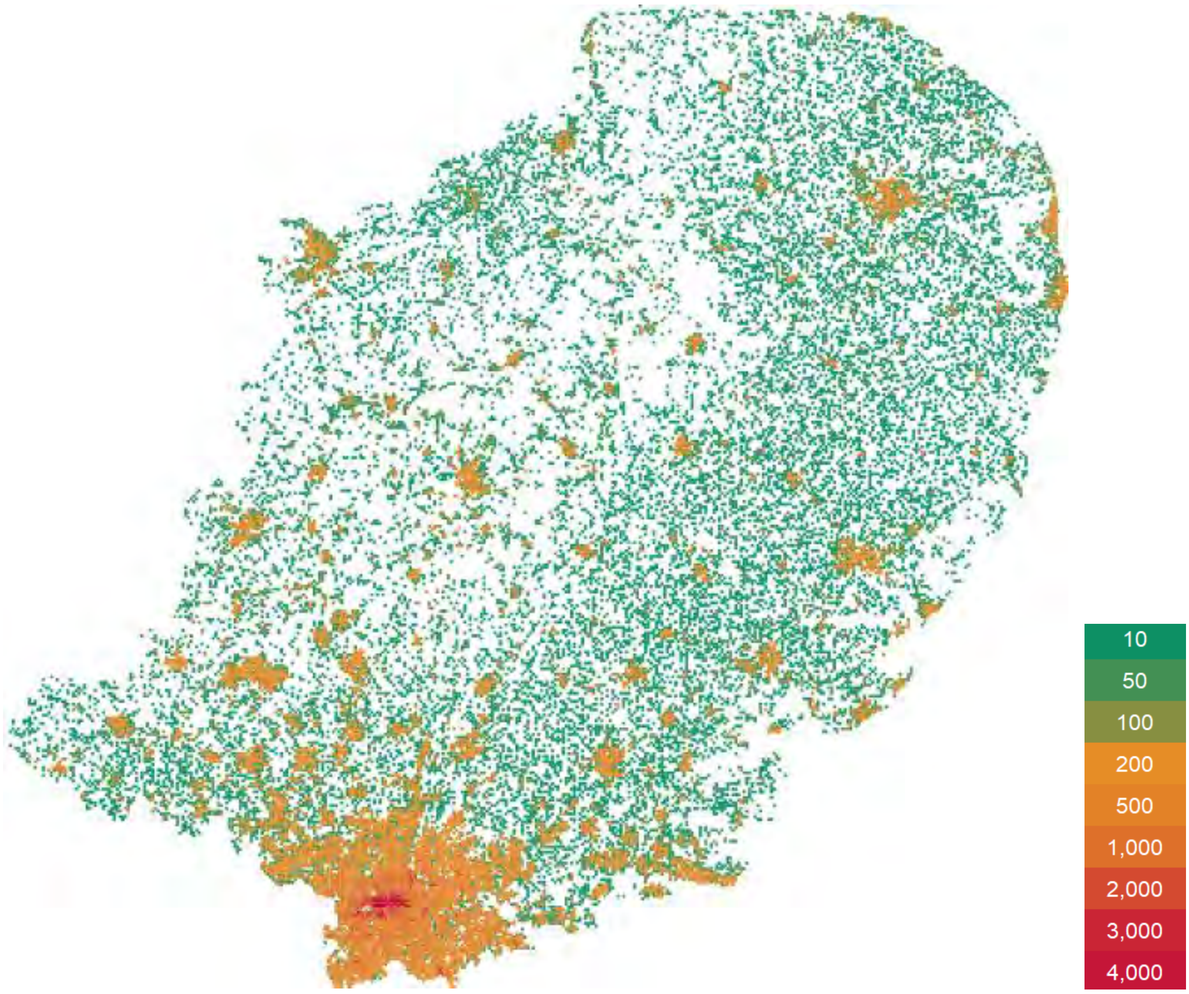


Figure 1.2: LPN and EPN service cables, low and high voltage networks and distribution transformer losses density in MWh/year.km$^2$

Some basic information related to network statistics for the area under consideration is presented in Table 2.

Table 2. LPN and EPN networks characteristics

| LV and HV network statistics | LPN | EPN |
|---|---|---|
| **LV length, '000 km** | **22.6** | **48.7** |
| **DTs, '000** | **17.5** | **67.5** |
| **HV length, '000 km** | **12.0** | **38.5** |
| **Losses, %** | **3.0-4.8** | **3.6-5.4** |

Data related to the LPN and EPN LV and HV network characteristics in each area was analysed. Figure 1.2 presents overall LV and HV loss densities per square kilometre ($km^2$) which is associated with unit area (500 x 500 $m^2$). It can be concluded that higher loss densities tend to be associated with urban and more densely populated areas or regions with a significant amount of non-residential demand.

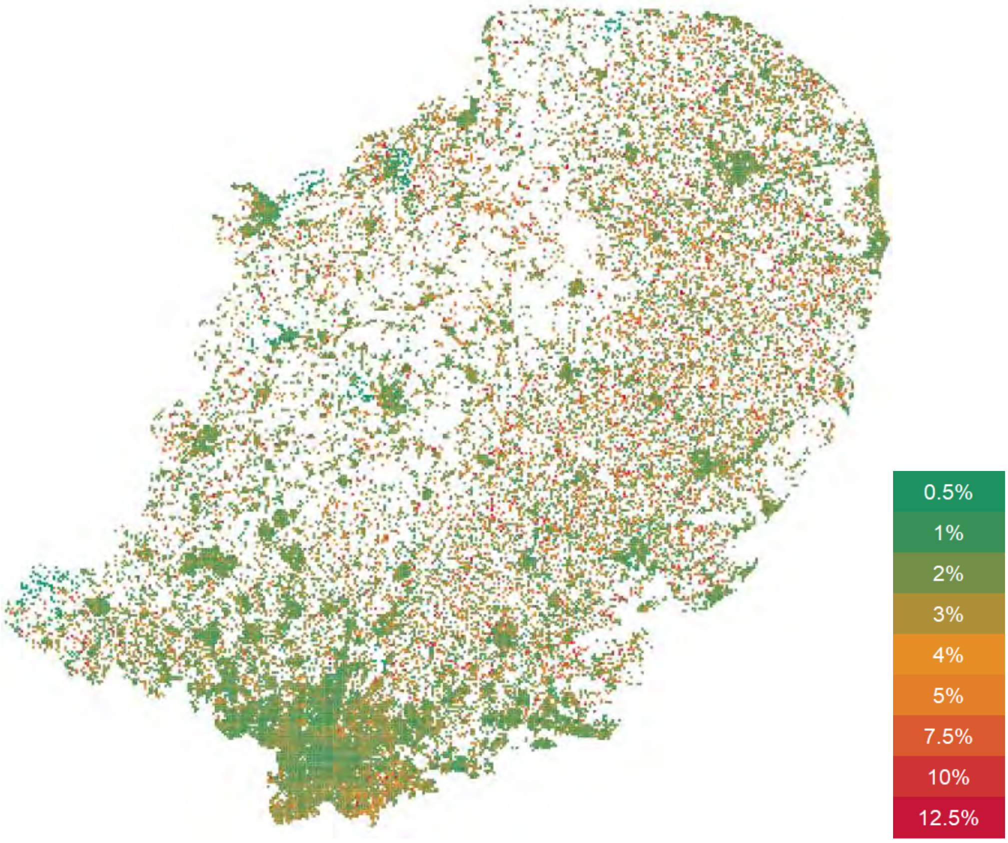


Figure 1.3: LPN and EPN service cables, low and high voltage networks and distribution transformer losses in percentage terms

However, LV and HV loss expressed in relative terms (percentages) are more evenly distributed, as can be observed in Figure 1.3. Relatively high level of percentage losses are observed throughout the network. High loss percentages indicate areas of relatively low network efficiency, which is also observed throughout the network. LV network percentage losses, however, tend to be high in areas with a high level of loss density, as depicted in Figure 1.4.

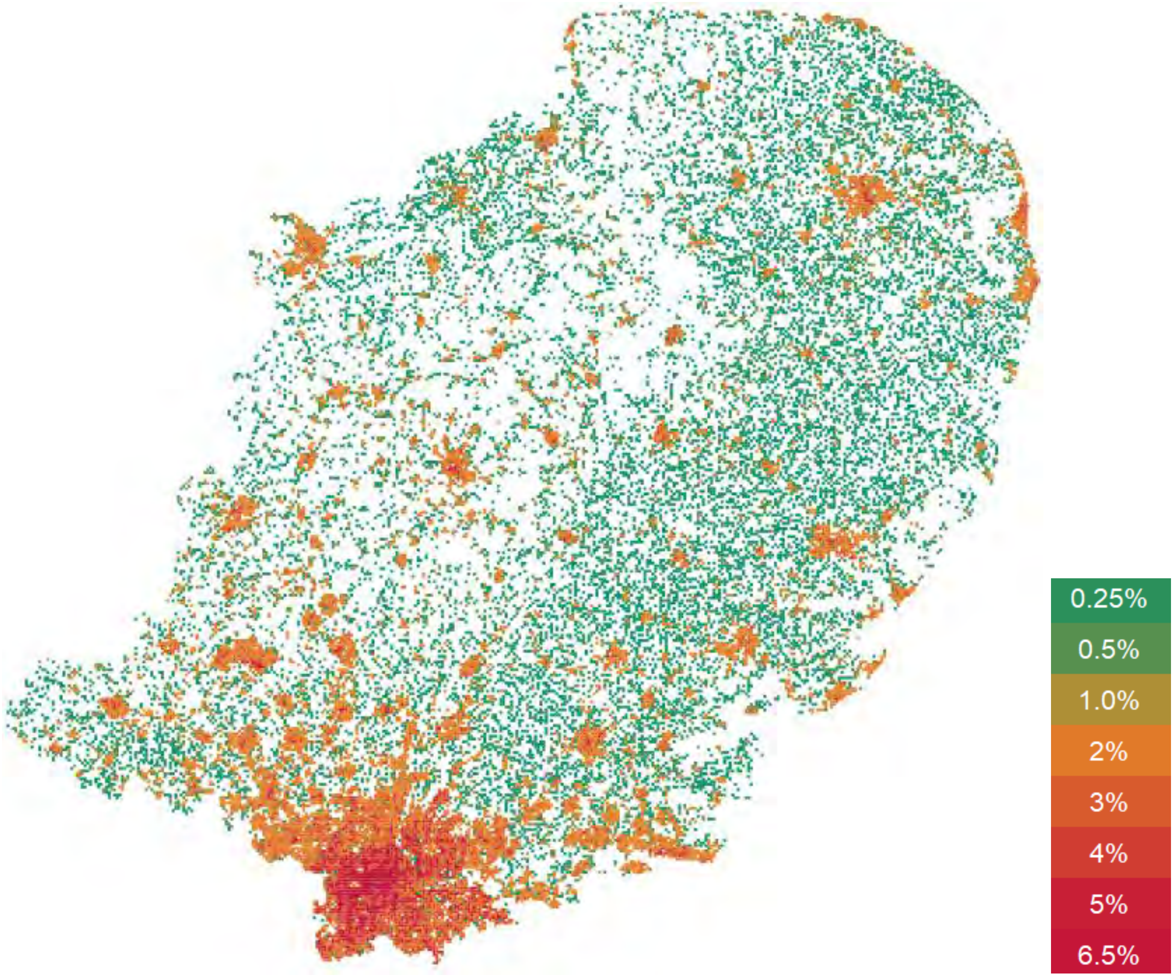


Figure 1.4: LPN and EPN low voltage network losses in percentage terms

It is clear that loss heat map representation of absolute and relative loss distribution and intensity levels in the network provide a valuable visual aid in identifying key critical regions in the system. For the first time, the analysis and quantification of network losses is based on a detailed network model of the entire UK Power Networks areas, as opposed to previous representations based on representative distribution networks only.

The next sections elaborate on various loss drivers, and how these influence losses. These drivers require different interventions to reduce losses, and heat maps serve as a high-level guide to steer network operators' loss mitigation activities.

## 1.3 Analysis of losses

The LPN and EPN network data were used to assess losses in different network segments. The results of this analysis are shown in Figure 1.5. As presented in Figure 1.5 (top right) losses attributable to service cables and LV networks are larger in LPN, due to higher utilisation levels. Total losses attributable to HV networks are higher in EPN than in LPN due to longer network length. It can be observed that load-related losses in DTs are higher in LPN while no-load losses are larger in EPN. Hence, transformer sizing could be enhanced in LPN, while addressing fixed losses in EPN would yield the best benefits. Overall, the total absolute losses are a bit higher in EPN, due to the greater HV losses.

In relative terms, however, HV network losses tend to be lower in the LPN area (0.69% min, 0.96% max), as compared to EPN (1.01% min, 1.76% max), as it can be observed in Figure 1.5 (top left). Relative LV network losses, including service cable losses, on the contrary tend to be higher in LPN (LPN: 1.57% min, 2.73% max; EPN: 1.71% min, 2.39% max). The share of LV losses tend to be higher in the LPN when compared to the EPN area (Figure 1.5). EHV/HV, EHV, 132/EHV and 132 kV network losses represents up to 25% (in min case) or less than 20% (in max case) of the overall losses. Given that more than 75% of total losses are in LV and HV networks, focus of the analysis is on these segments of the network.

DT associated losses have a similar profile, both in absolute and relative terms (Figure 1.5), with the dominance towards higher load related losses in LPN (LPN: 0.51% min, 0.71% max; EPN: 0.43% min, 0.61% max), and higher no-load related losses in EPN (LPN: 0.27% min, 0.38% max; EPN: 0.48% min, 0.67% max).

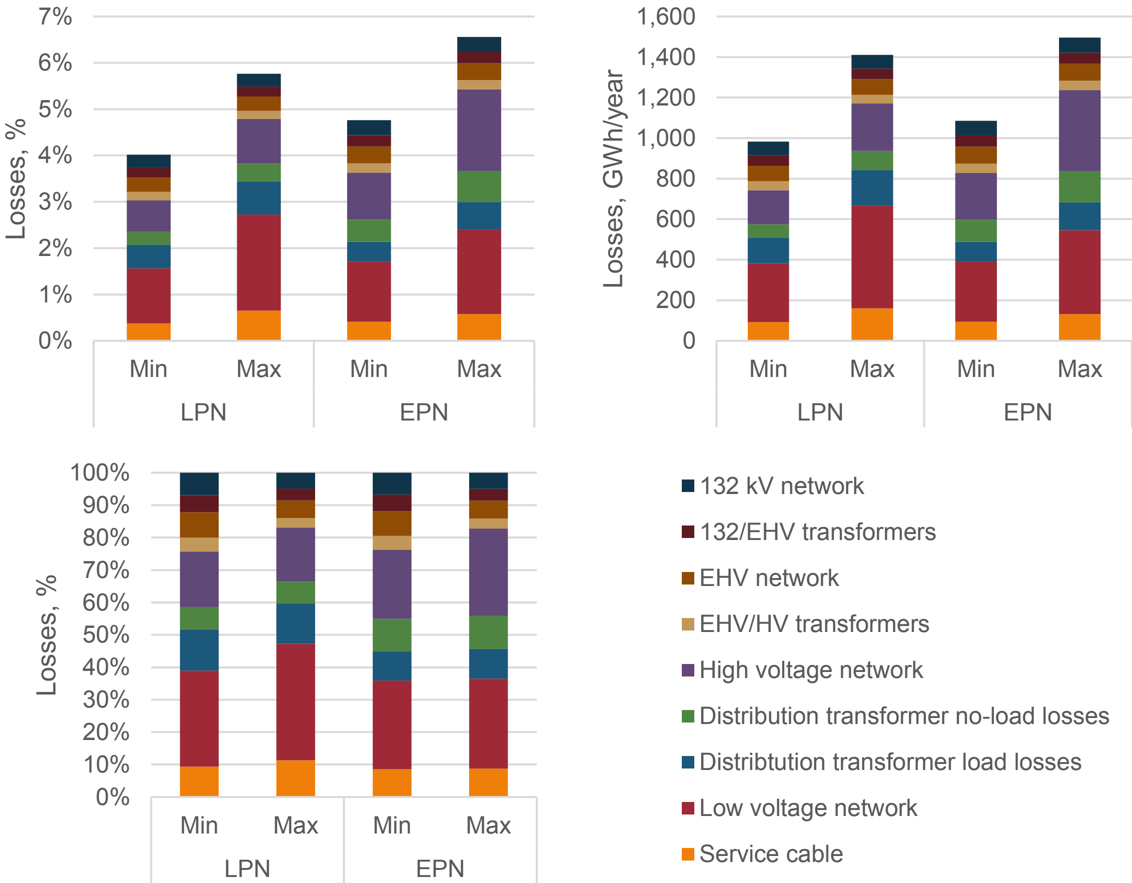


Figure 1.5: Comparison of LPN and EPN network losses

In the LPN licence area, annual losses are between 1,000-1,400 GWh/year. In EPN, annual losses are between 1,100-1,500 GWh/year.

Further analysis was undertaken to understand how HV feeder length and utilisation affect losses. Figure 1.6 shows that EPN feeders are longer, but that feeder losses in LPN are higher. Hence, this analysis reveals that losses are predominantly driven by feeder lengths in EPN, and that intensive asset utilisation drives losses in LPN.

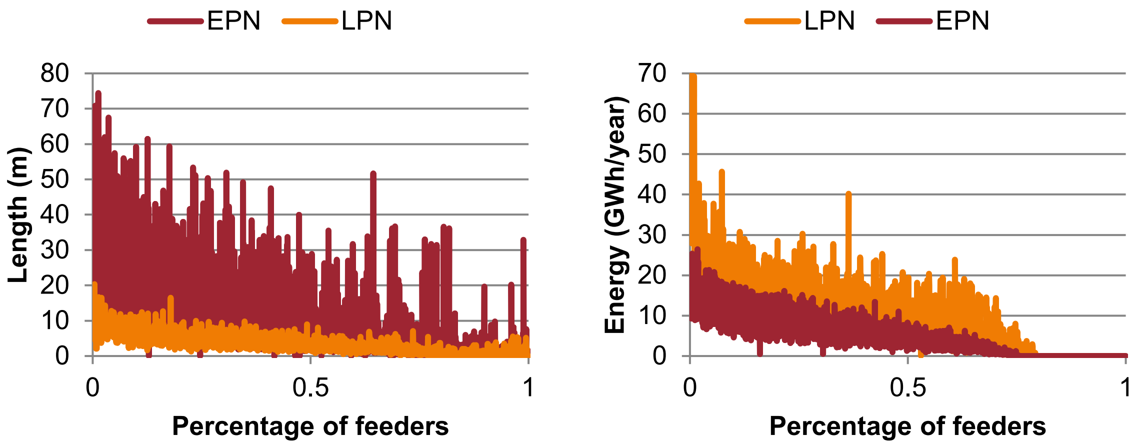


Figure 1.6: Comparison of LPN and EPN HV losses for length (left) and energy (right)

With regard to DT peak utilisation rates (Figure 1.7): in the LPN area 19% of transformers have a peak utilisation of 70% or more, while in the EPN area the share comes down to only about 4%. This reinforces previous observations made on DT associated load and no-load loss rates. Some further conclusions can also be drawn with respect to overall losses, in a more detailed elaboration broken down by population density.

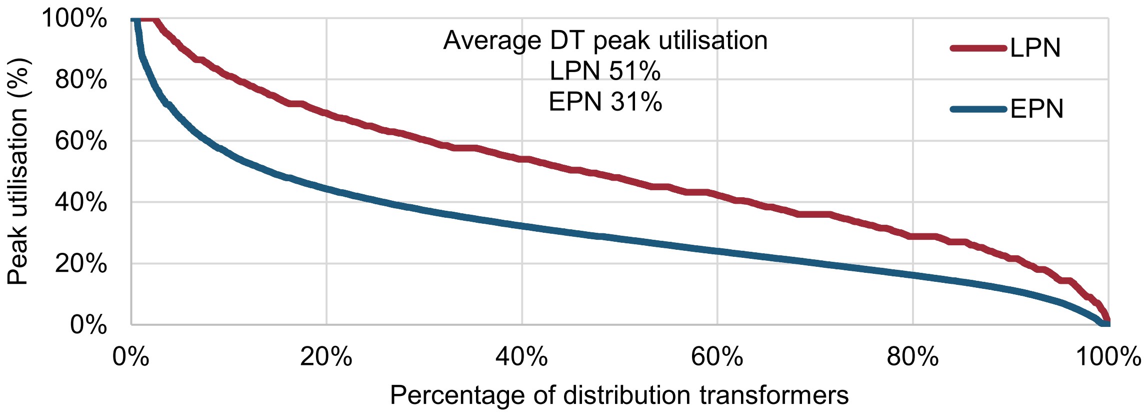


Figure 1.7. LPN and EPN DT Peak Utilisation

Networks in both LPN and EPN regions are categorised by population density (number of customers per km$^2$) and the relative losses attributable to differing levels of population density are analysed. The applied classifications are <150 customers/km$^2$, <750 customers/km$^2$, <5000 customers/km$^2$, and >5000 customers/km$^2$. The results of the analysis of the relation between population distribution and losses are shown in Figure 1.8 and Figure 1.9. Here the X-axis represents customer densities in LPN and EPN. The Y-axes represent total losses for all squares with relevant customer density shown in Figure 1.2 in GWh/year and percentage proportion of losses per voltage level, respectively. Losses in areas with a customer density of 750 customers/km$^2$ or higher are significantly pronounced in the LPN area. The EPN area is predominantly characterised by losses associated to the areas with customer densities of less than 150 customers/km$^2$ and a customer density of between 750-5000 customers/km$^2$.

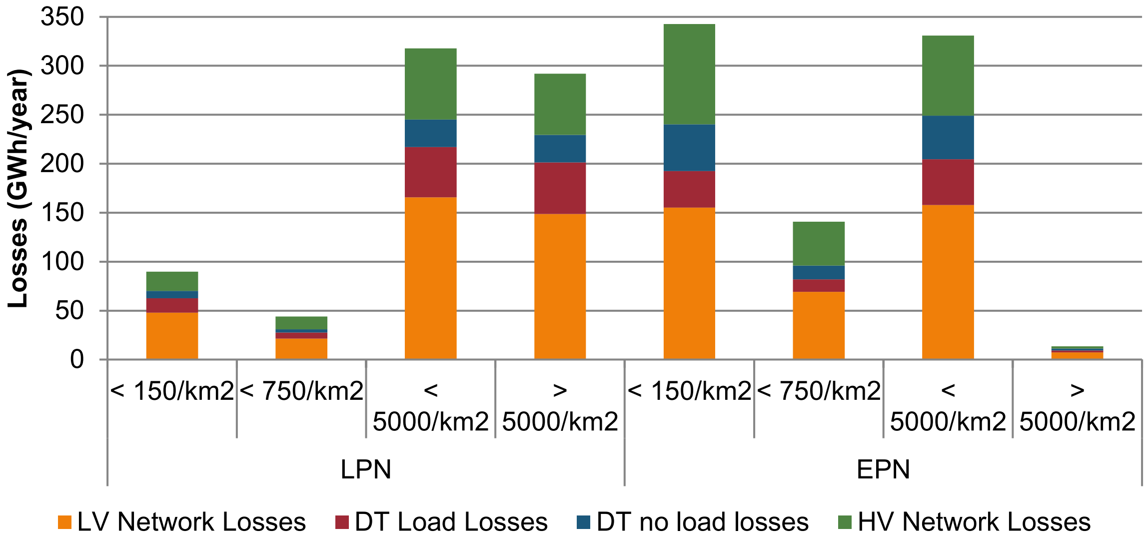


Figure 1.8: Comparison of LPN and EPN network losses with population density

Figure 1.9 shows that losses, expressed in percentage values, are fairly evely distributed across the various regions and classes. The proportion of HV network losses, however, is greater in lower customer density areas. In those areas, customers are typically supplied from shorter LV networks and relatively longer HV networks. This suggests that the loss-driver is loading, rather than length of LV circuits. Proportions of DT losses tend to be lowest in EPN with a customer density of between 150-750 customers/km$^2$. It can be seen that DT losses increase with increase in customer density as well as with decrease in customer density in which case pole mounted transformers (PMTs) would be predominantly used. Hence, the use of amorphous steel transformers in overhead networks with PMTs could be an economically efficient way of managing DT no-load losses.

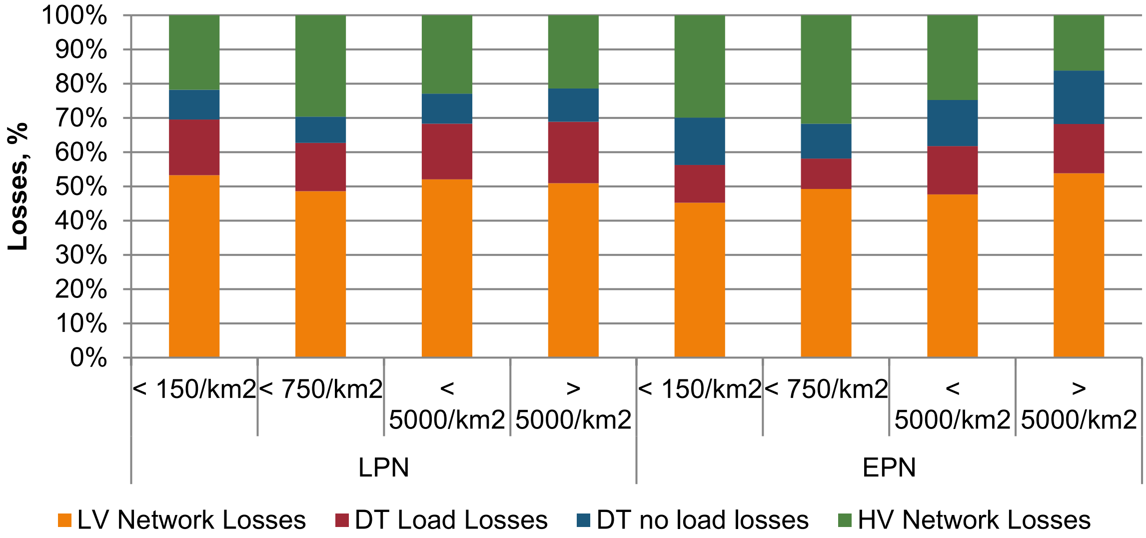


Figure 1.9: Comparison of LPN and EPN network losses with population density

For networks where GMT are installed, distribution transformer losses increased proportionately in line with customer density while HV network losses decrease. Hence, the use of low-loss transformers across higher customer density areas to reduce losses could be more economically efficient. However, for areas with less than 150 customers per km$^2$ distribution transformers tend to be smaller which leads to an increase in distribution transformer losses. Potentially, in these areas, losses could be mitigated by achieving a better balance between load and no-load losses.

## 1.4 Impact of sample rate on losses modelling

Calculated losses vary depending on the sampling rate of the load measurements used in the calculation. Depending on load variability, a different sampling rate might produce different calculated losses. A service cable case study is carried out to analyse the impact of high load variability on the losses calculation. About 5,000 daily load profiles are considered, each with a sampling rate of one measurement per five seconds. For each daily five-second load profile, daily losses are calculated for different service cable sizes. Following this, half-hourly profiles are calculated by averaging the five-second profiles. Calculation of losses is repeated for half-hourly profiles. For each profile, the ratio of daily losses calculated for the two sampling rates are calculated and shown in Figure 1.10.

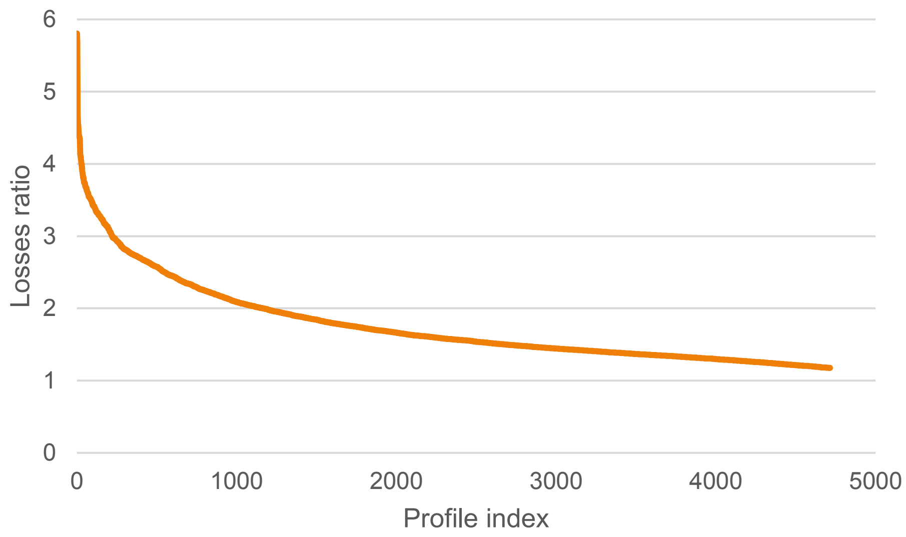


Figure 1.10. Losses multiplier representing ratio of daily losses calculated with five-second and half-hourly profiles

It can be seen that for a few profiles the losses ratio is greater than 4. In this case, losses calculated using half-hourly profile could be as much as a quarter below the five-second sample value. For the considered profiles the losses ratio was between 1.2 and 5.8. The losses ratio average is about 1.9. To improve the accuracy of service cable losses calculations when half-hourly or hourly profiles are used, a losses factor of 1.9 or similar is recommended.

## 1.5 Summary

In this study, analysis and quantification of network losses is based on a detailed network model of all three of UK Power Networks' licence areas, from low voltage networks to grid supply points[9]. This is in stark contrast to the previous analysis of network losses that was based on the application of representative distribution networks[10].

Losses heat maps are developed to identify regions of each of UK Power Networks' licence areas in which magnitude of losses are most significant. Relevant data is obtained form the studies carried out using the LOIM tool. It is clear that losses heat map representations of

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[9] Specifically, the scope of Loss Operation & Investment Model (LOIM) is extended to enable quantification of network losses under different scenarios and loss-reduction strategies

[10] Imperial College London and Sohn Associates, Management of electricity distribution network losses, supported by WPD and UKPN, 2014

absolute and relative loss distribution and intensity levels in the network provide a valuable visual aid in identifying key critical regions in the system.

Furthermore, the analysis carried out demonstrates that more than 75% of network losses are associated with LV networks, HV networks and distribution transformers. Overall, 36-47% of the total losses are in LV networks, 9-13% and 7-10% of losses are associated with distribution transformer load related losses and no-load losses respectively, 17-27% are in HV networks and finally 17-24% of total losses are in primary transformers, grid transformers, EHV networks, and 132 kV networks. Understanding the contribution of different network sections to the total losses will be important when analysing the cost effectiveness and potential impact of different loss management strategies.

Service cable losses modelling needs to account for sampling-rate load variability. It is recommended that a losses ratio of 1.9 is used in the first instance when half-hourly profiles are used.

# 2 Distribution of losses across network segments

The aim of this section is to understand which loss-drivers were most significant in which types of networks in order identify loss-reduction techniques that are likely to be most effective in different types of network.

## 2.1 Overall network-level analysis

Figure 2.1 shows losses for more than 4,000 UK Power Networks radial HV feeders. It can be seen that there is a relatively small number of HV feeders that have high losses. Losses on some HV feeders could be up to about 1,000 MWh/year.

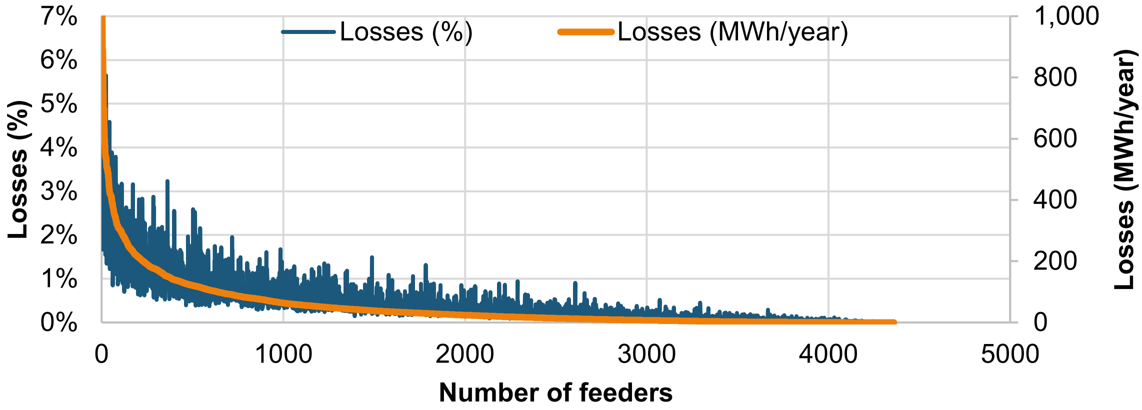



Figure 2.1. UK Power Networks radial HV feeder losses

Figure 2.2 shows losses for LV networks. It can be seen that relatively fewer LV networks are characterised with high losses. This could be used for prioritisation of LV networks for potential losses reduction. LV network losses could be up to about 85 MWh/year.

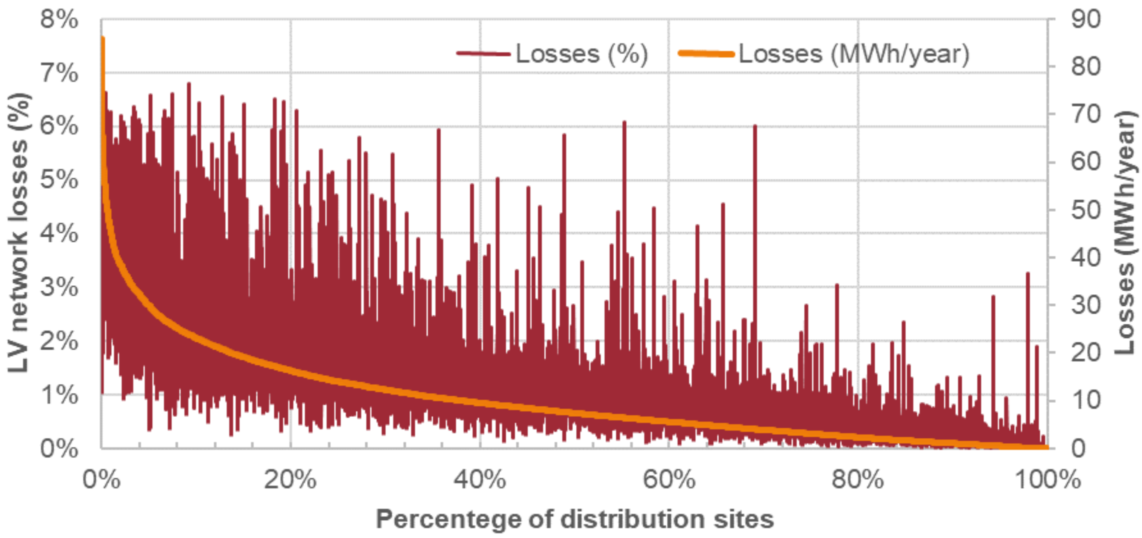



Figure 2.2. LV network losses

## 2.2 LV network analysis

The relationship between the length of LPN LV circuits and their losses was analysed, with the results shown in Figure 2.3. The X-axis shows the total length of LV networks supplied from a distribution site which contains one or more distribution transformers. The Y-axis shows the annual losses per distribution site. The correlation between LPN LV network losses and circuit length is shown below. Generally, the losses increase with length of the networks, although there are some relatively short networks characterised with high losses, and some long networks with low losses. The former would typically have few customers with high loads, and the latter many customers with low loads.

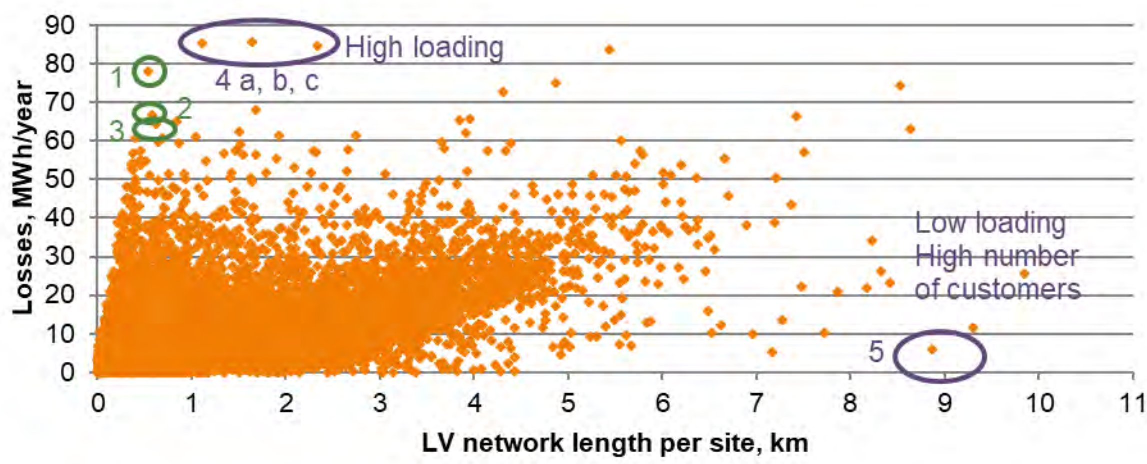



Figure 2.3: Correlation of LPN LV network losses and length per site

The scatter plot is very wide and two categories of LV networks could be considered:

- High losses and short networks
  - Cases 1 and 3: single-connected customer at the end of a feeder with relatively high loading will result in relatively high losses; for comparison, uniformly distributed load for a large number of customers would results in one third of the losses
  - Case 2: small numbers of connected customers with relatively high loading (about double of the cases 1 and 3)
  - Cases 4 (a, b and c): relatively high loading and longer network length for customers of a) same type, b) two types and c) four customer types (domestic and non-domestic; unrestricted and multi tariff),
- Low losses and long networks
  - Case 5: Relatively low loading and high number of customers.

## 2.3 HV feeders with high losses

The LOIM was used to quantify losses on UK Power Networks HV feeders. An illustration of two feeders of similar length is shown in Figure 2.4. Feeder 2 has slightly higher overall peak load. However, Feeder 1 is characterised by 50% higher losses due to the long first section to the first load point, while for Feeder 2 the loading is clustered in the middleof the feeder. Load distribution is a key driver for losses on these two feeders.

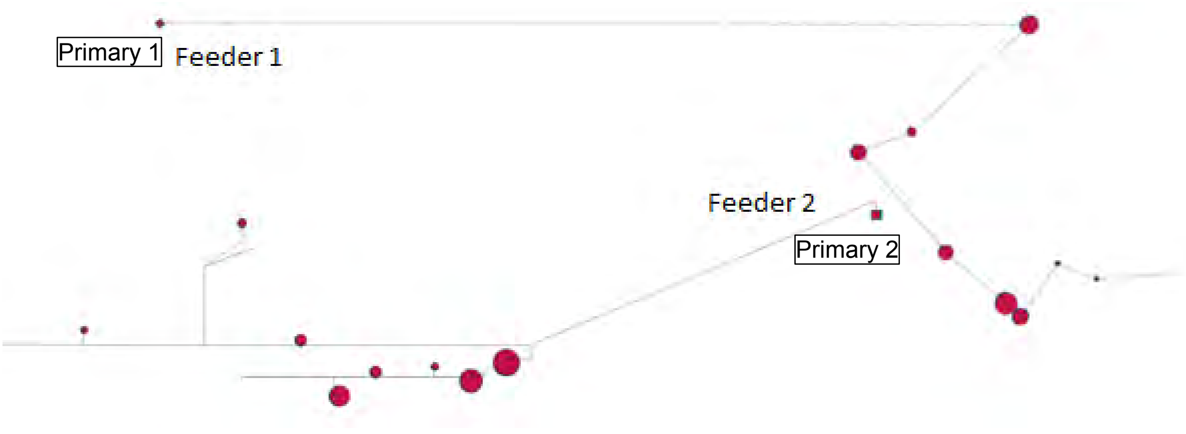



Figure 2.4: Illustration of two UK Power Networks HV feeders of similar length

UK Power Networks HV feeders are disaggregated into groups according to losses levels. Assuming that losses mitigation measures have higher potential in feeders with relatively high losses, the focus of the investigation is on those feeders. Figure 2.5 shows the UK Power Networks HV feeders with losses greater than 550 MWh/year. The X-axis shows feeder reference, the Y-axis shows losses in MWh/year and secondary Y-axis shows percentage of losses. Feeders were analysed to understand drivers for relatively high losses and whether there is any similarity between feeders.

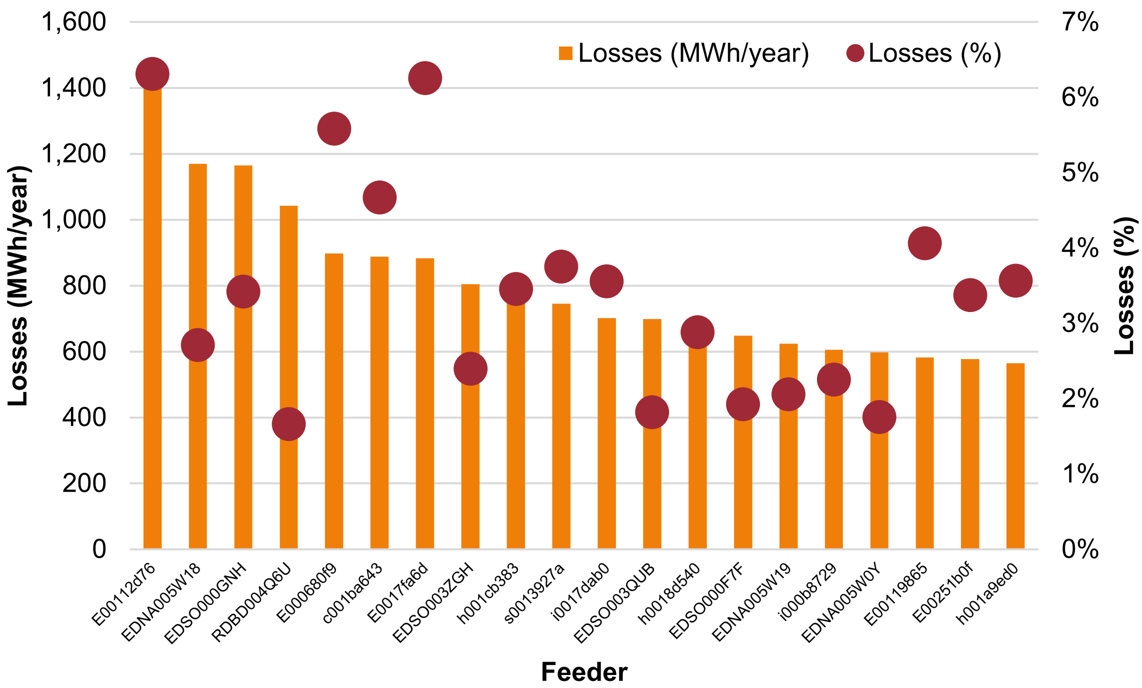



Figure 2.5. UK Power Networks HV feeders with high losses (>550 MWh/year)

The EPN HV feeder with the highest losses is feeder E00112d76. It is 55 km long as denoted and schematically illustrated in Figure 2.6. Total maximum peak demand is 4.7 MW and annual losses are 1,422 MWh/year or 6%. It is relatively long feeder with two major branches. On one of the major branches, relatively high load is located towards the end of feeder, which results in relatively high losses.

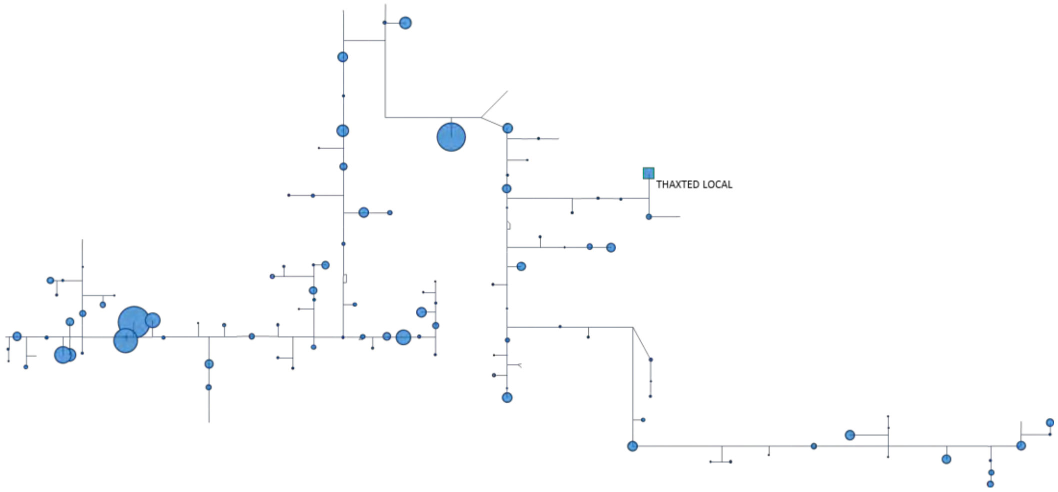



Figure 2.6. Schematic illustration of EPN HV feeder with the highest losses supplied from the Thaxted local primary substation. Size of circles represent level of peak load. Total feeder length is 55 km.

Figure 2.7 shows LPN HV feeder EDNA005W0Y, which is characterised by relatively high absolute volume of losses. The feeder length is 9.9 km and peak loading is 7.4 MW. It is shorter than the one in Figure 2.6 but loading is greater. There is a long 3.5 km section of feeder to the first load point, which is about a third of the total feeder length. 71% of feeder losses are generated on this section alone. All load points are located towards the end of the feeder which results in relatively high losses of 598 MWh/year or about 2%.

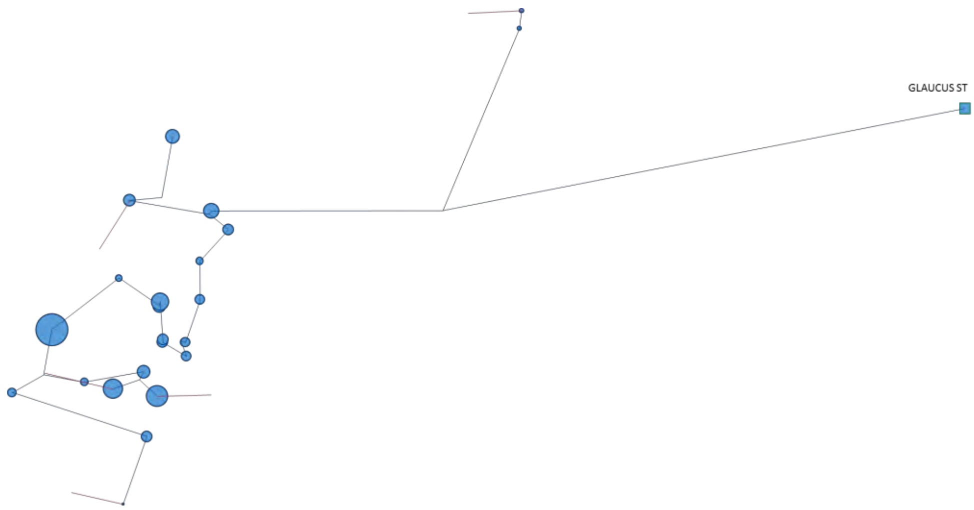



Figure 2.7. Illustration of LPN HV feeder with high losses supplied from Glaucus street primary substation. Size of circles represent level of peak load. Red lines represent sections where NOP is located. High proportion of losses are generated on first sections of feeder before the first load point connection.

Figure 2.8 shows SPN HV feeder, EDSO003ZGH, which has comparatively high losses. It is relatively long (16.8 km) and characterised by a high load of 7.2 MW at peak. The annual losses are 804 MWh/year, or about 2.5%. About 65% of total losses are generated in the first two sections of the feeder.

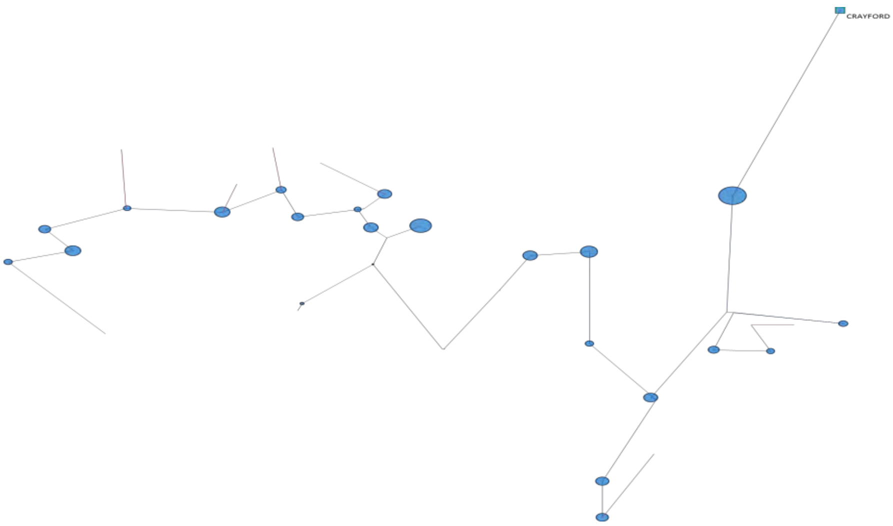


Figure 2.8. Illustration of SPN HV feeder with relatively high losses supplied from Crayford primary substation.

Each of the high losses feeders investigated have widely differing characteristics. It is therefore difficult to derive standard templates that could enable simple feeder and network classifications and easy understanding of effectiveness of different losses mitigation measures.

## 2.4 Cluster-based network analysis

In order to draw general conclusions about different types of network, an analysis of the LV and HV network dataset for UK Power Networks' three licence areas was carried out to identify network categories, or "clusters" of networks with similar characteristics, which can then be used to represent different types of network. For example, it might be that many circuits fall into the category of being a certain length, having a certain number of customers, where the customers are mostly of a certain Elexon load type. It was anticipated that this clustering could be used to identify types of network in different licence areas and to identify types of loss interventions that may be beneficial for different network types.

The dataset contains 30,470 Pole Mounted Transformer (PMT) networks and 53,198 Ground Mounted Transformer (GMT) networks. The following parameters are used on a per-DT basis: total transformer rating and maximum demand, total overhead and underground circuit length, total number of connected customers and their mix in terms of the Elexon profiles (DU, DR, NDU, NDR), and area type (rural, semi-rural, semi-urban, and urban). A neural networks-based self-organising map was used to disaggregate networks into 16 clusters for PMT networks and 16 clusters for GMT networks.

The feeder parameters considered are: feeder length, number and rating of pole and ground mounted distribution transformers, load distribution along feeder, feeder losses. All parameters are split onto main and latter part of feeder.

A Self Organising Map (Neural Networks) approach is used to disaggregate feeders into clusters. Networks supplied from pole (PMT) and ground mounted transformers (GMT) are considered separately and they are split into 16 clusters each. For PMT 10 clusters are selected and for GMT 12 clusters. Table 3 shows overall characteristics of networks aggregated into different clusters. For example, in cluster RN1 there are 2,063 distribution transformers and LV networks. Total DT rating is about 206 MVA and maximum demand about 100 MVA. Total LV network OH and UG length is about 582 and 406 km respectively. Total connected domestic unrestricted and multi-tariff customers are 14,173 and 14,303, respectively. Total connected non-domestic unrestricted and multi-tariff customers are 2,033 and 2,475, respectively. The area type is predominantly rural. Most of UK Power Networks' licence areas are contained in three clusters: RN17, RN15 and RN8, to which more than 6,000 LV networks are assigned.

Table 3. Characteristics of network clusters; DT: distribution transformer, LV: low voltage, OH: overhead line, UG: underground cable, DU: domestic unrestricted, DR: domestic multi-tariff, NDU: non-domestic unrestricted, NDR: non-domestic multi-tariff, area type index 1: rural, 2: semi-rural, 3: semi-urban, 4: urban

| Cluster | Number of DTs | Total DT Rating kVA | Total DT Maximum Demand kVA | Total LV Circuit OH Length km | Total LV Circuit UG Length km | Number of DU Customers | Number of DR Customers | Number of NDU Customers | Number of NDR Customers | Avg Area Type Index |
|---|---|---|---|---|---|---|---|---|---|---|
| RN1 | 2,063 | 205,985 | 99,960 | 582 | 406 | 14,173 | 14,303 | 2,033 | 2,475 | 1.2 |
| RN2 | 604 | 133,965 | 59,240 | 135 | 198 | 5,601 | 5,301 | 990 | 1,054 | 1.3 |
| RN3 | 2,463 | 61,630 | 10,622 | 340 | 95 | 4,607 | 3,672 | 955 | 1,020 | 1.1 |
| RN4 | 1,623 | 162,225 | 41,165 | 682 | 500 | 34,580 | 34,327 | 1,941 | 2,744 | 1.5 |
| RN5 | 3,191 | 1,597,216 | 604,496 | 255 | 5,657 | 185,038 | 484,828 | 10,744 | 16,706 | 2.6 |
| RN6 | 4,645 | 2,321,650 | 970,018 | 103 | 9,585 | 771,312 | 157,930 | 46,633 | 12,086 | 2.1 |
| RN7 | 5,821 | 582,100 | 117,267 | 1,363 | 989 | 29,042 | 23,357 | 5,709 | 5,587 | 1.1 |
| RN8 | 6,004 | 300,200 | 59,796 | 1,096 | 562 | 16,990 | 13,736 | 3,588 | 3,679 | 1.1 |
| RN9 | 3,433 | 1,711,240 | 1,132,356 | 80 | 4,249 | 185,547 | 132,749 | 34,428 | 16,724 | 2.4 |
| RN10 | 2,062 | 1,028,975 | 816,695 | 9 | 5,455 | 587,467 | 57,203 | 44,004 | 5,491 | 3.1 |
| RN11 | 2,383 | 693,326 | 314,189 | 265 | 3,227 | 102,634 | 277,267 | 4,202 | 6,424 | 2.5 |
| RN12 | 2,007 | 2,013,400 | 716,050 | 16 | 2,608 | 113,492 | 147,576 | 20,975 | 20,022 | 2.5 |
| RN13 | 744 | 149,130 | 38,432 | 330 | 385 | 24,176 | 20,329 | 1,242 | 1,431 | 1.6 |
| RN14 | 4,896 | 771,075 | 284,192 | 592 | 2,767 | 86,074 | 87,124 | 6,099 | 5,918 | 1.4 |
| RN15 | 6,549 | 2,008,767 | 528,835 | 755 | 5,452 | 219,110 | 179,842 | 13,533 | 12,511 | 1.6 |
| RN16 | 2,083 | 417,680 | 81,984 | 428 | 481 | 11,468 | 9,554 | 2,845 | 2,811 | 1.2 |
| RN17 | 8,897 | 4,448,595 | 1,008,228 | 452 | 8,946 | 388,951 | 278,113 | 40,834 | 29,403 | 1.8 |
| RN18 | 3,529 | 2,773,730 | 559,405 | 42 | 3,249 | 146,259 | 138,333 | 23,082 | 16,540 | 2.3 |
| RN19 | 3,005 | 2,370,000 | 1,085,088 | 13 | 2,696 | 107,821 | 87,508 | 36,220 | 14,657 | 3.0 |
| RN20 | 2,570 | 128,513 | 58,535 | 523 | 254 | 7,366 | 6,929 | 1,532 | 1,824 | 1.1 |
| RN21 | 1,485 | 1,180,400 | 470,277 | 6 | 3,361 | 374,799 | 49,859 | 32,045 | 5,071 | 3.1 |
| RN22 | 2,925 | 44,854 | 12,160 | 264 | 83 | 4,209 | 3,317 | 775 | 774 | 1.1 |

Table 4 presents characteristics of selected neural network-derived clusters.

Table 4. Characteristics of selected pole (PMT) and ground mounted transformer (GMT) clusters; OH: overhead line, UG: underground cable, D: domestic, ND: non domestic, DU: domestic unrestricted, DR: domestic multi-tariff, NDU: non-domestic unrestricted, NDR: non-domestic multi-tariff

| Cluster | Mounting | Description |
|---|---|---|
| RN1 | PMT | Rural, OH:UG=1.5:1, D:ND=6:1 |
| RN2 | PMT | Rural, OH:UG=1:1.5, D:ND=5.5:1 |
| RN3 | PMT | Semi-rural, UG, D:ND=16:1, DU predominantly |
| RN4 | PMT | Semi-rural, OH:UG=1.5:1, D:ND=15:1 |
| RN5 | GMT | Semi-urban, UG, D:ND=24:1, DU:DR=1:2.5, NDU:NDR=1:1.5 |
| RN6 | GMT | Semi-rural, UG, D:ND=16:1, DU:DR=5:1, NDU:NDR=4:1 |
| RN7 | PMT | Rural, double rating and maximum demand compared to cluster 1, OH:UG=1.5:1, D:ND=5:1 |
| RN8 | PMT | Rural, OH:UG=2:1, D:ND=4:1 |
| RN9 | GMT | Semi-rural, UG, D:ND=6:1, NDU:NDR=2:1 |
| RN10 | GMT | Urban, UG, D:ND=14:1, NDU:NDR=8:1 |

| Cluster | Mounting | Description |
|---|---|---|
| RN11 | GMT | Semi-urban, OH:UG=1:12, D:ND=36:1 |
| RN12 | GMT | Semi-urban, UG, D:ND=6:1 |
| RN13 | PMT | Semi-rural, OH:UG=1:1, D:ND=25:1 |
| RN14 | GMT | Rural, OH:UG=1:5, D:ND=14:1 |
| RN15 | GMT | Semi-rural, OH:UG=1:7, D:ND=15:1 |
| RN16 | PMT | Rural, OH:UG=1:1, D:ND=3.5:1 |
| RN17 | GMT | Semi-rural, OH:UG=1:20, D:ND=10:1 |
| RN18 | GMT | Semi-rural, UG, D:ND=7:1 |
| RN19 | GMT | Semi-urban, UG, D:ND=4:1, NDU:NDR=2.5:1 |
| RN20 | PMT | Rural, OH:UG=2:1, D:ND=4:1 |
| RN21 | GMT | Urban, UG, D:ND=11:1, DU:DR=8:1, NDU:NDR=6:1 |
| RN22 | PMT | Rural, UG, D:ND=6:1 |

For example, cluster RN1 is characterised with the ratio of overhead lines to underground cable lengths is 1.5:1 i.e. overhead lines are 50% longer than underground cables. Domestic customers are predominantly connected with a domestic to non-domestic customer ratio of 6:1. Average parameters for each cluster are used to create representative networks. Figure 2.9 shows representative network annual losses.

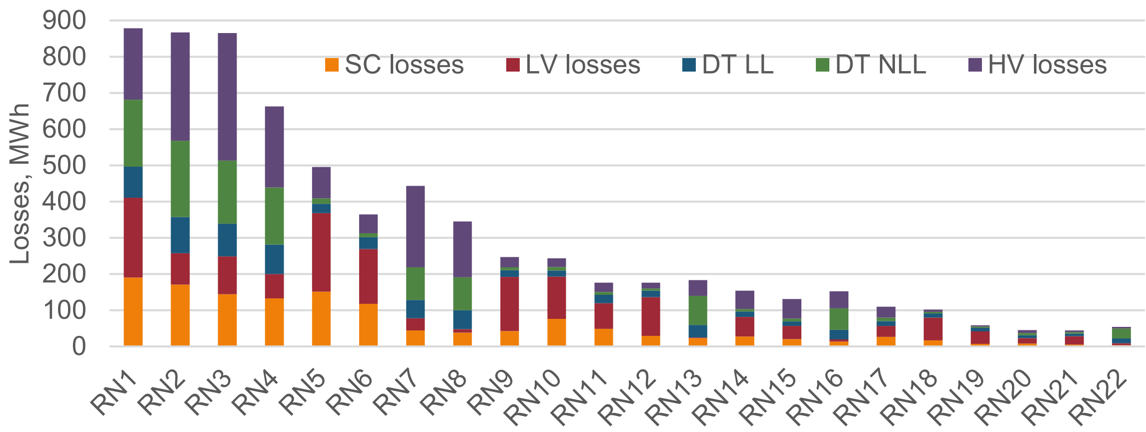



Figure 2.9. Breakdown of annual losses for representative networks

The highest losses are expected on average in rural network types, RN1 and RN2, and in those networks supplying residential areas as well as in semi-urban network types also supplying residential areas. All three network types are supplied from pole mounted transformers.

Figure 2.10 shows percentage of losses for representative networks.

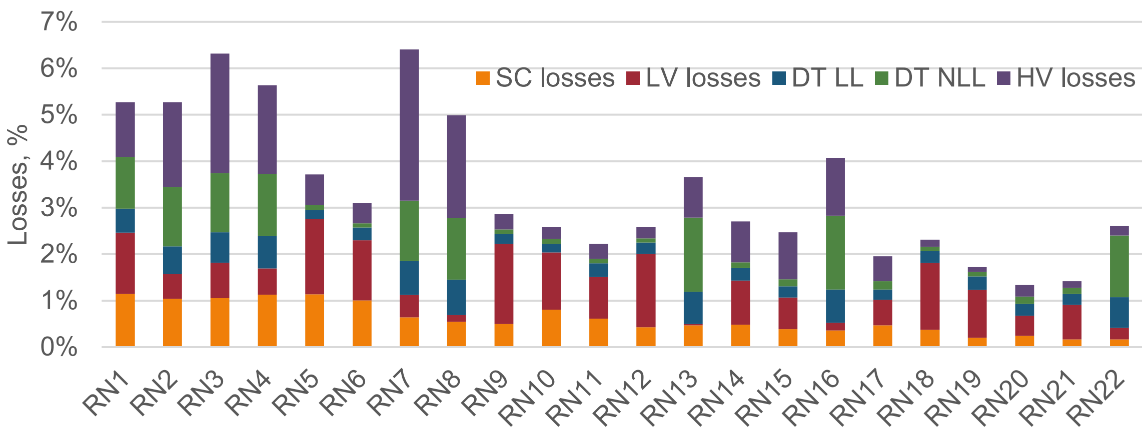



Figure 2.10. Breakdown of annual losses in percentages for representative networks

RN7, RN3 and RN4 have relatively high losses compared to the energy transported. All network types are supplied from PMTs and are predominantly domestic. This is consistent with the observation that HV losses are relatively high in those networks.

Figure 2.11 shows the relative share of loses in representative networks across the network.

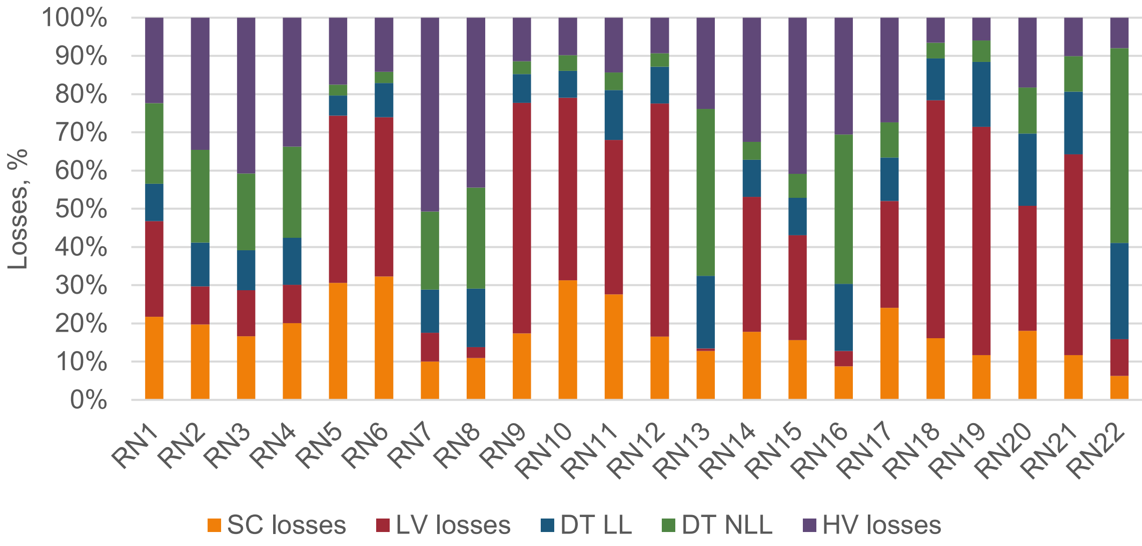



Figure 2.11. Losses source for clusters

Given the greater customer and load density in urban areas, greater losses per square kilometre were observed. In urban areas, LV network losses are dominant while in rural areas HV network losses are dominant. RN22, RN13 and RN16 type networks are characterised with relatively short networks and hence distribution transformer losses are dominant.

Representative networks describe averages very well, but do not appropriately describe extreme cases, i.e. feeders with very high losses that may be targeted for loss reduction. Hence for these cases it is more beneficial to analyse real rather than representative networks.

## 2.5 Summary

Network losses are strongly influenced by demand density and circuit length, because of this detailed analysis of network loading and correlation with feeder lengths in different areas is carried out. UK Power Networks operate a wide range of network types, from rural areas, as in parts of Norfolk and Suffolk, to very densely populated urban areas like London. These areas have corresponding peak demand density ranging from very low (0.05 MW/km$^2$) in rural areas to very high density (137 MW/km$^2$) in urban areas. In this context, the average utilisation of distribution transformers varies between 51% and 38% in LPN and EPN areas respectively. Furthermore, the analysis carried out demonstrated that 20% of distribution transformers in LPN are characterised by peak utilisation greater than 70%. On the other hand, only about 4% of distribution transformers in EPN area are highly loaded.

Detailed power flow modelling revealed that feeders in the LPN area deliver on average 50% more energy than in the EPN area, while the circuits in LPN region are on average about 60% shorter than in the EPN. This analysis demonstrated that the losses in LPN area are primarily driven by high network utilisation, while in EPN losses are driven by long feeder lengths. Overall, losses in LV networks are comparable (for the minimum case) in both areas or slightly greater in LPN area (for the maximum case) even though the LPN LV network is significantly shorter but characterised by higher loading. On the other hand, losses in HV networks are greater in the EPN area.

The analysis also demonstrated that the magnitudes of losses vary significantly across the networks. A relatively small number of feeders are accountable for the majority of losses. Detailed modelling demonstrated that 20% of feeders are responsible for 70% of HV network losses. Similarly, more than 50% of losses in LV networks are in only 20% of feeders. This clearly demonstrates that the loss reduction schemes in HV networks needs to target only a relatively small proportion of the feeders characterised by high losses, in order to achieve cost-effective loss mitigation.

Based on an advanced neural networks methodology, UK Power Networks' networks are classified into 22 clusters according to the number of connected customers and their mix, LV network length and construction, and distribution transformer mounting, rating and loading. Average parameters for each cluster are quantified and corresponding representative networks created, ranging from rural to urban networks and the related loss performance assessed. However, as the significant amount of losses turned out to be associated with a relatively small number of very specific feeders, generic feeders with average parameters may not provide appropriate evidence to inform the development of effective losses reduction strategies.

# 3 Identification of potential operational strategies for loss reduction

## 3.1 Optimisation of Normally Open Point locations

HV and LV distribution networks are typically operated with a radial topology. However, in order to minimise customer minutes lost under fault conditions, the networks are designed in such a way that the load can be supplied from another adjacent feeder via a Normally Open Point (NOP) switch. In this study, we investigated the benefits of optimising the NOP locations to minimise network losses.

We then compared the losses in the original network and the losses in the network with optimised locations of NOP switches. The study is performed on an actual UKPN HV network with the key parameters shown in Table 5.

Table 5 Key data of the network used in the study

| | |
|---|---|
| Primaries | 114 |
| Feeders | 2,286 |
| Nodes | 31,063 |
| Branches | 29,676 |
| Total lines length (km) | 7,826 |
| Loads | 17,809 |
| Total Load (MVA) | 5,537 |
| NOPs | 2,828 |

The optimisation of NOP locations results in the closer to average loading of each feeder, leading to lower losses. This is demonstrated in Figure 3.1 where the loading of all 2,286 feeders in the basecase with the orginal NOPs and the case with optimised NOPs is presented.

In the case with the original NOP positions, the loading of feeders varies in a larger range compared to the loading of feeders in the case with optimised NOP locations. This explains the larger network losses in the base case since losses are a quadratic function of network loading. By optimising the locations of NOP switches, the system loads can be allocated more evenly to the feeders resulting in lower losses. Some of the spare feeders, which were not initially loaded, might become loaded after the proposed optimal NOP locations are deployed. This approach is used to minimise losses by determining the optimal location of NOPs.

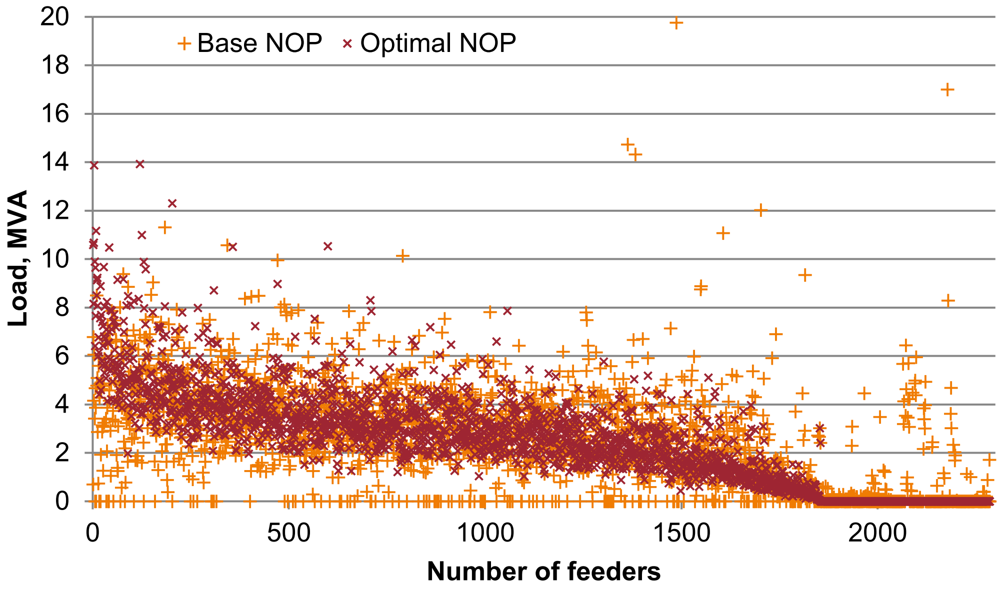



Figure 3.1 HV feeder loading in the base case and the optimised case.

The optimisation of NOP locations also changes the variation of the feeder lengths. The feeder length expressed in km for the feeders analysed in the study is shown in Figure 3.2. The range of variation is lower when compared to the non-optimised case. This also explains the reduced losses in the optimised case.

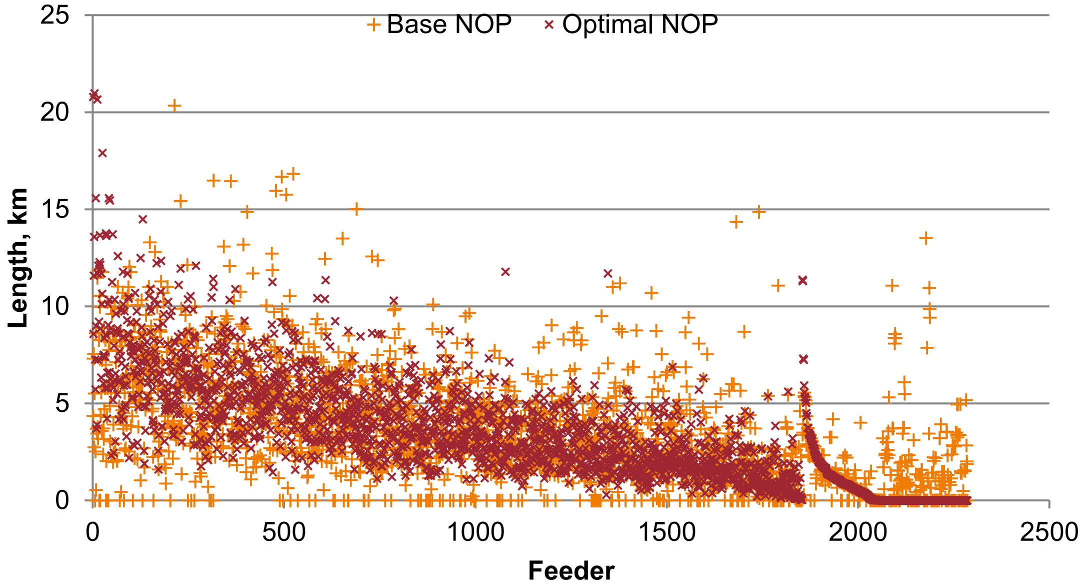



Figure 3.2 HV feeder length in the base case and the optimised case.

Figure 3.3 presents the losses on all feeders under the base case and the optimised case. The results for the optimised case (corresponding to the brown line) express the number of feeders having losses above the level indicated in the Y-axis e.g. around 14% (about 300 out of about 2,100 feeders with losses greater than zero) of the feeders exhibit losses higher than 50 MWh/year.

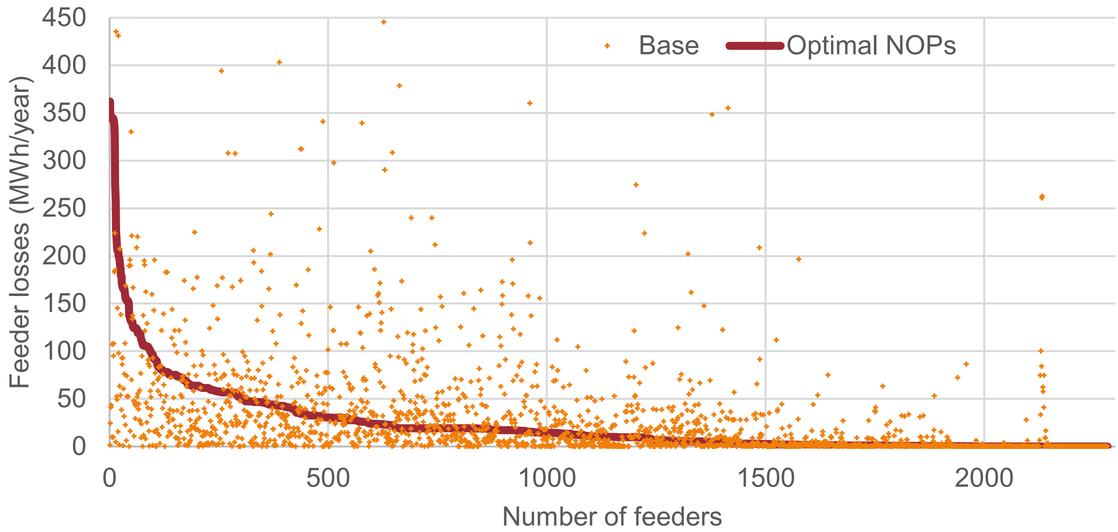



Figure 3.3. HV feeder losses in the base case and the optimised case.

The overall losses in the system are presented in Table 6, which demonstrates that the optimisation of the NOP locations leads to a 17% reduction of losses in the network.

Table 6.Reduction of total losses in the optimised case.

| | Base Case | Optimised Case | Reduction |
|---|---|---|---|
| Losses (MWh/year) | **67,398** | **56,253** | **17%** |

The above findings imply that the determination of the locations of NOP should consider the effect of losses. The simple approach proposed in this study yields a 17% reduction of total losses if the locations of the NOP switches are optimised. The equivalent capitalised value is between £5.4-8.9m.

With smart HV network switched potential for losses reduction might be even greater and achieve meshed network losses of 50,839 MWh/year which yields additional losses reduction of 8% and the equivalent value between £2.6-4.3m.

## 3.2 Power factor correction

Since both active and reactive power flows contribute to the overall losses in an AC network, a useful strategy in reducing losses lies in minimising the reactive power load. In this context, the following study investigates the impact of installing power factor correction to reduce the reactive power load.

Since the exact value of the present power factor in the actual networks employed in these studies is not accurately known, in order to comprehensively evaluate the benefits of power factor correction, a number of studies assuming four different levels of power factor improvement are carried out. The first scenario assumes that the base (present) power factor is 0.95 and after the deployment of power factor correction, the power factor is equal to 1. The second, third and fourth scenario assume that the reference power factor is 0.9, 0.85 and 0.8

respectively. For each scenario, the network losses in the base case are compared against the losses in the case with power factor correction. The study is carried out for real UKPN LV and HV networks. It should be noted that the observed losses reduction does not include improvement of losses at all upstream levels. Hence, shown losses reduction represent conservative value and, hence, the same losses reduction in LV networks would have greater impact then losses reduction on HV networks.

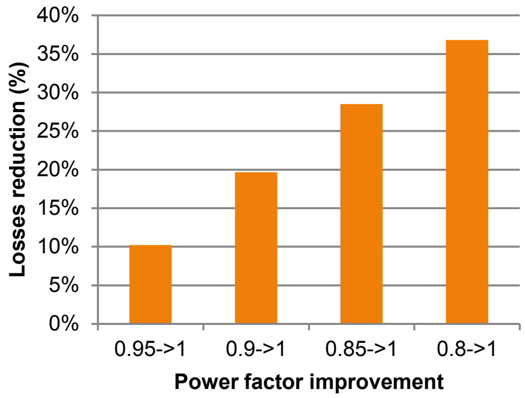



Figure 3.4. Impact of power factor correction on LV and HV networks

The reduction of losses under each of these scenarios is presented in Figure 3.4. The results demonstrate that power factor improvement can achieve very significant reduction of losses, which, depending on the scenario, can reach up to 29% reduction in LV networks and 36% reduction in HV networks. As expected, the benefit is higher when the power factor of the base case is lower. However, even if the base power factor is 0.95, the achieved reduction of losses is still substantial, i.e. 7% in LV networks and 10% in HV networks.

In order to further investigate the benefits of power factor correction on different UKPN networks, studies have been carried out on selected SPN, EPN and LPN feeders. For each type of feeders, two power factors are considered, i.e. 0.85 and 0.95. The benefits of improving the power factor from 0.85 to 0.95 in each type of network are shown in Figure 3.5, Figure 3.6 and Figure 3.7.

The graphs are explained as follows. The x-axis shows HV feeders used in the studies; the HV feeders are ranked according to the reduction of peak losses (in absolute values) - from the highest to the lowest- achieved by the deployment of power factor correction. In this way, the study can help network planners to determine priority areas where power factor correction strategies would have significant benefits. The 1st y-axis (left) denotes the annual losses in MWh/year. The brown and orange lines denote the losses for the case with 0.85 and 0.95 power factor respectively. The relative reduction in losses due to power factor improvement from 0.85 to 0.95 is expressed by the green line (referring to the 2nd y-axis).

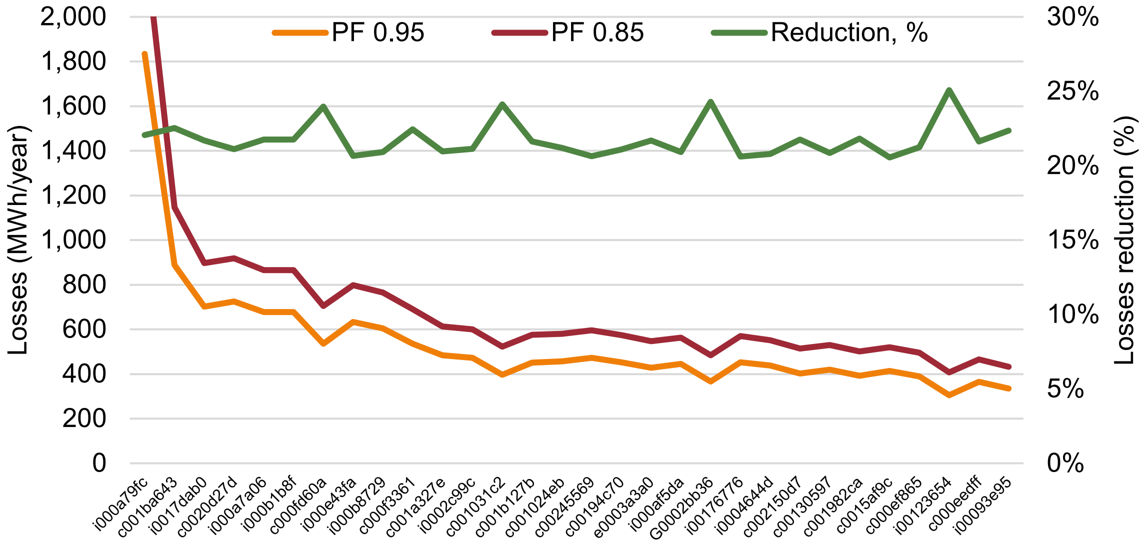



Figure 3.5. List of SPN feeders ranked by reduction of losses achieved by power factor improvement.

The study on the SPN feeders (Figure 3.5) demonstrates that the range of losses reduction that can be expected is between 20% and 25%. The results demonstrate that prioritising the deployment of the power factor correction to feeders with high losses (in absolute values) would be most beneficial. However, even for the feeders with lower absolute losses (right hand part of the graph), the level of losses reduction is still significant. If the power factor is improved from 0.85 to 0.95, the corresponding losses reduction for the above 30 feeders is more than 50 MWh/year. It should be noted that actual power factor is unknown and it is recommended to investigate further the above selected HV feeders.

The results for the EPN feeders (Figure 3.6) offer the same kind of conclusions. The range of losses reduction is between 20% and 27% and this reduction is consistent across all feeders irrespectively to the level of their absolute annual losses. The losses reduction for the specified 30 feeders is more than 115 MWh/year.

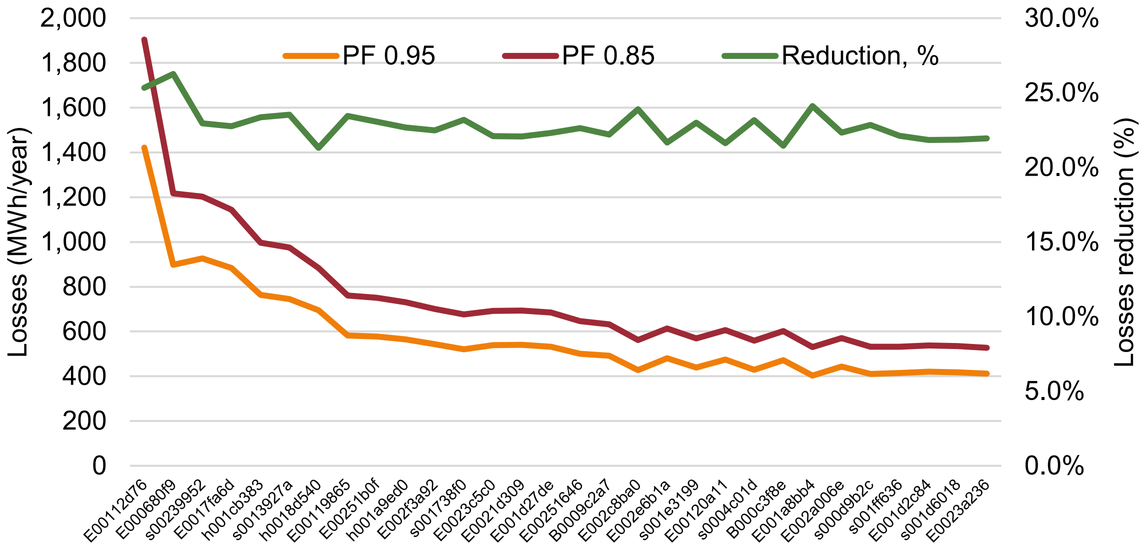



Figure 3.6. List of EPN feeders ranked by reduction of losses achieved by power factor improvement.

For the LPN feeders, the losses reduction seems to be consistent around 20%.

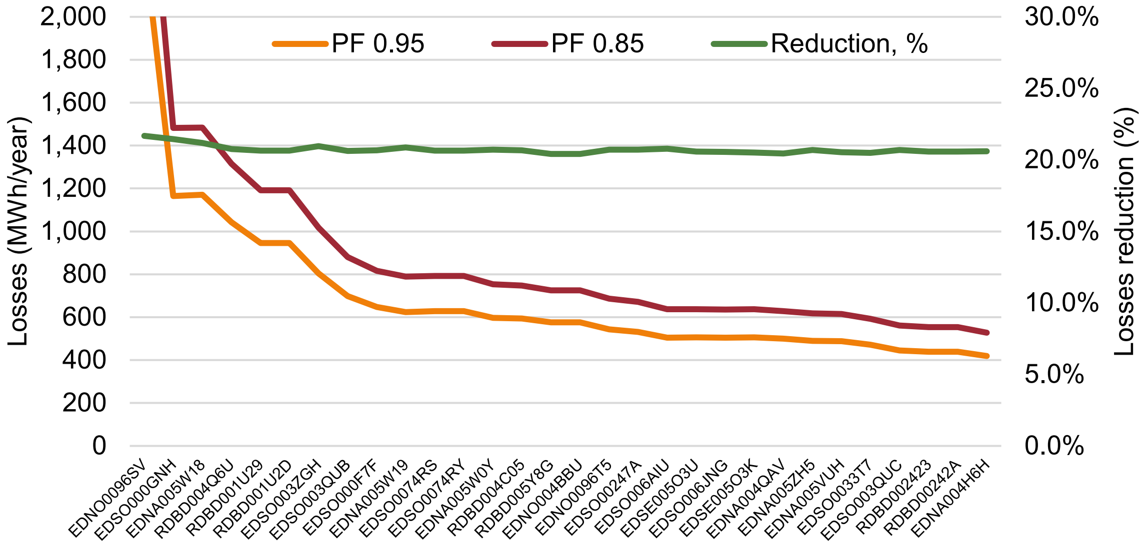



Figure 3.7. List of LPN feeders ranked by reduction of losses achieved by power factor improvement.

We can conclude that the deployment of power factor correction on the UKPN networks could potentially achieve significant benefits in terms of reduction in network losses. The study shows that the expected loss reduction lies between 20% and 27% if the power factor can be improved from 0.85 to 0.95. Losses are reduced at least about 110 MWh/per for each of the above 30 feeders.

**Single point power factor compensation**

In order to improve the power factor, investing in reactive power compensation may be beneficial. The location and the size of the compensation are critical factors to be considered in order to maximise the benefit of this investment. In this study, we have employed mathematical analysis to determine the optimal location and size of the reactive power compensation under certain assumptions.

Figure 3.8 illustrates a feeder with uniformly distributed load along its length and the change in current due to the deployment of compensation. This model is used for deriving the location and size of the compensation achieving the lowest losses.

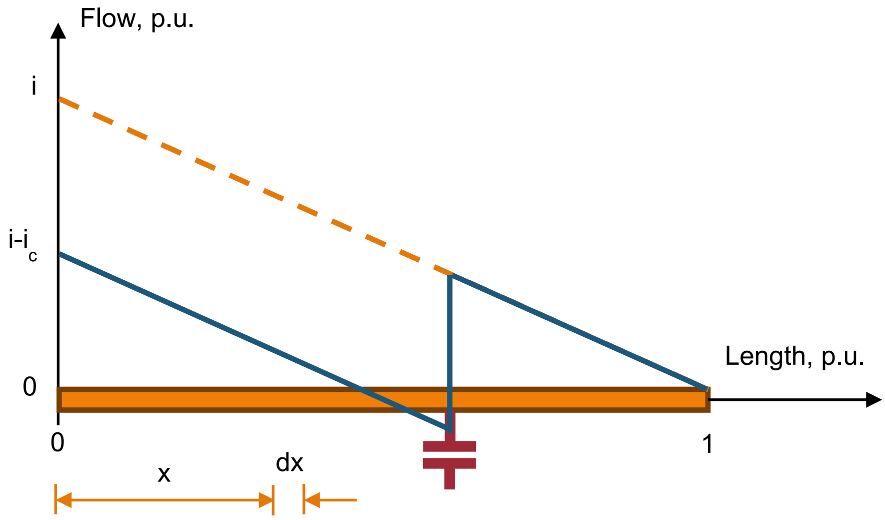



Figure 3.8. Illustration of radial feeder and change in current due to deployment of compensation.

In this study, we assume that the distribution network is operated in radial topology and the load is distributed uniformly across the feeder. In this case, the feeder losses without any reactive compensation can be formulated as follow:

$$P_{Loss} = \int_0^1 3 \cdot r \cdot dx \cdot \ [i \cdot (1-x)]^2 = r \cdot i^2 \quad (1)$$

Considering reactive compensation, the formula can be re-written as follows:

$$P_{Loss}^c = 3 \cdot r \left\{ \int_0^{l_c} [i \cdot (1-x) - i_c]^2 dx + \int_{l_c}^1 [i \cdot (1-x)]^2 dx \right\} = r \cdot i^2 + 3 \cdot r \cdot l_c \cdot i_c \cdot [(l_c - 2) \cdot i + i_c] \quad (2)$$

Thus, the losses reduction can be derived from the difference between (1) and (2):

$$\Delta P_{Loss} = P_{Loss} - P_{Loss}^c = 3 \cdot r \cdot l_c \cdot i_c \cdot [(2 - l_c) \cdot i - i_c] \quad (3)$$

In order to determine the optimal location and size of the single point reactive compensation, the optimality condition to the 1st derivative of (3) are derived. Based on this approach, the optimal location of the reactive compensation is at 2/3 of the feeder length (with the substation used as the reference point) and the optimal size of the compensation is 2/3 of the reactive power load.

This strategy is then analysed, i.e. installing a single point reactive compensation in this optimal location and with this optimal size, on selected HV UKPN feeders in LPN, SPN, and EPN areas. For each type of feeders, two cases are simulated, i.e. a base case without compensation (assuming a power factor of 0.85) and a case with a single point reactive compensation with the above optimal characteristics.

The results corresponding to LPN feeders are presented in Figure 3.9. The x-axis shows the feeder IDs (sorted from high to low losses feeders) and the y-axis shows the annual feeder losses for the base case (corresponding to the orange line) and the case with optimised reactive compensation (corresponding to the brown line). The relative losses reduction is expressed by the green line. The results clearly indicate the significant benefits of reactive compensation as the losses at all feeders considered in this study decrease by more than 12%. This is equivalent to capitalised benefits between £28-46k for each of identified 30 feeders.

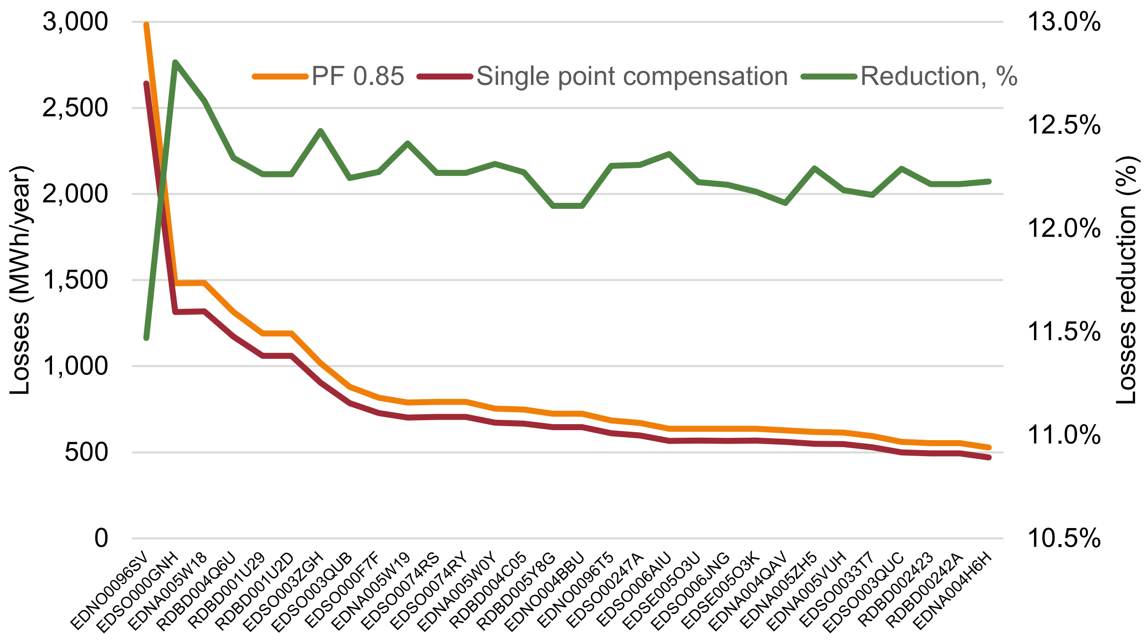



Figure 3.9 List of LPN feeders ranked by reduction of losses achieved by reactive power compensation.

In a similar fashion, the results of the study corresponding to the SPN feeders are presented in Figure 3.10. The results demonstrate that the deployment of reactive compensation can reduce losses about 12%. The capitalised value of savings for the first 30 feeders could be between £25-41k per feeder.

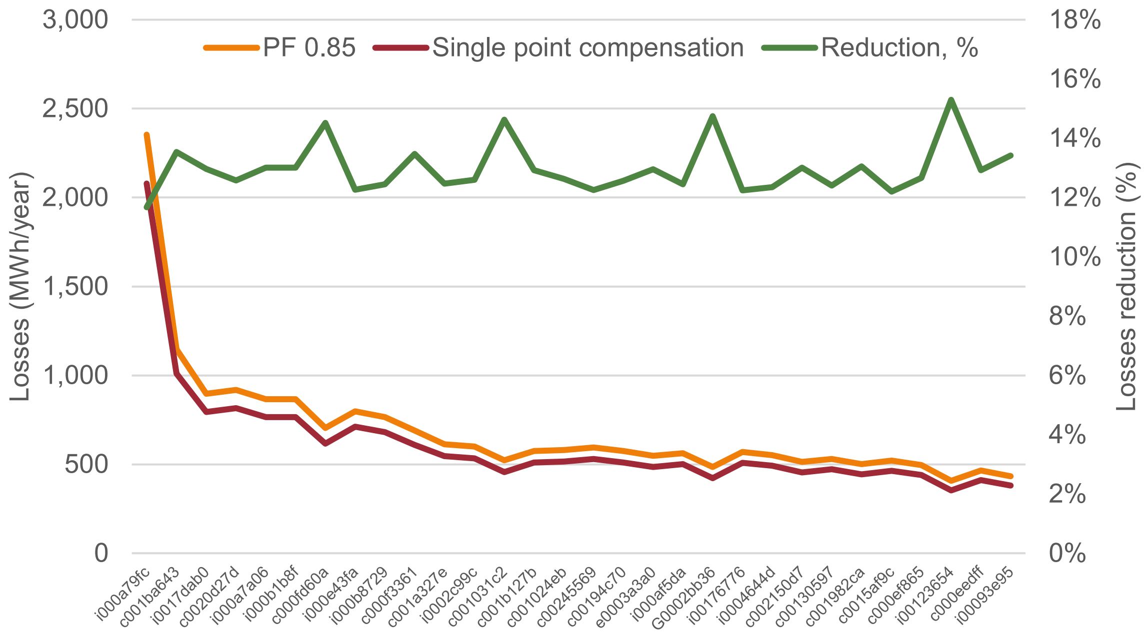



Figure 3.10 List of SPN feeders ranked by reduction of losses achieved by reactive power compensation.

The results of the study correspond to the EPN feeders are presented in Figure 3.11. The improvement in losses varies between 12% and 14%, with corresponding capitalised value per feeder being between £30-49k.

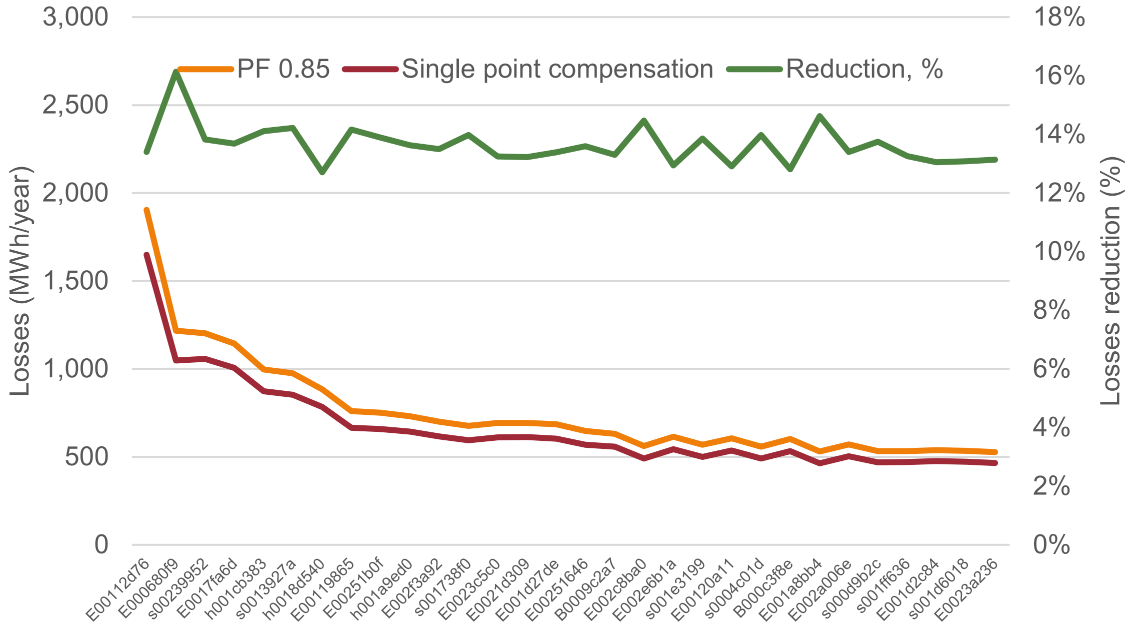



Figure 3.11 List of EPN feeders ranked by reduction of losses achieved by reactive power compensation.

Based on the presented results, it is clear that the deployment of reactive power compensation of suitably designed size and location could potentially achieve significant reduction of network losses, ranging from 12% to 14% in the examined studies.

Based on the above simple analysis, the optimal location is at 2/3 of the feeder length (with the substation used as the reference point) and the optimal size of the compensation is 2/3 of the reactive power load, for feeders with uniformly distributed load. Given that the load distribution may be different in reality, further analysis is required to determine the optimal location and size of reactive compensation.

## 3.3 Voltage control driven loss reduction

Another strategy for reducing losses investigated in this project is related to voltage control aimed at reducing electricity load. The rationale behind this strategy lies in the fact that some electricity loads are voltage dependent, such as motors, resistive heating, etc. By lowering the voltage, the power demand of may reduce, leading to reduction in network losses. The voltage control technology can be implemented at the system level by optimising position of tap-changing transformers or through the application of voltage optimisation technologies (e.g. powerPerfector) at the customer connection points.

For illustrating the potential impact of voltage control on network losses, studies have been carried out assuming that electricity demand is composed of constant power, constant current and constant impedance type loads. The study is performed on LV networks and HV feeders in EPN area. Losses in the base case (without voltage control) and the case with optimised voltage are presented in Figure 3.12 for LV networks and in Figure 3.13 for HV feeders.

The x-axis shows the feeder IDs (sorted from high to low losses feeders) and the y-axis shows the annual feeder losses for the base case (corresponding to the orange line) and the case with optimised voltage level (corresponding to the brown line). The results indicate that the benefits achieved by voltage control are relatively modest (around 5%). The corresponding capitalised value of loss reduction per site is between £1.5-2.4k. It should be noted that this corresponds to maximum benefit as calculation is conducted assuming constant impedance based demand model. For example, if voltage dependent load could be represented by one third constant power, one third constant current and one third constant impedance than changes in losses would be marginal.

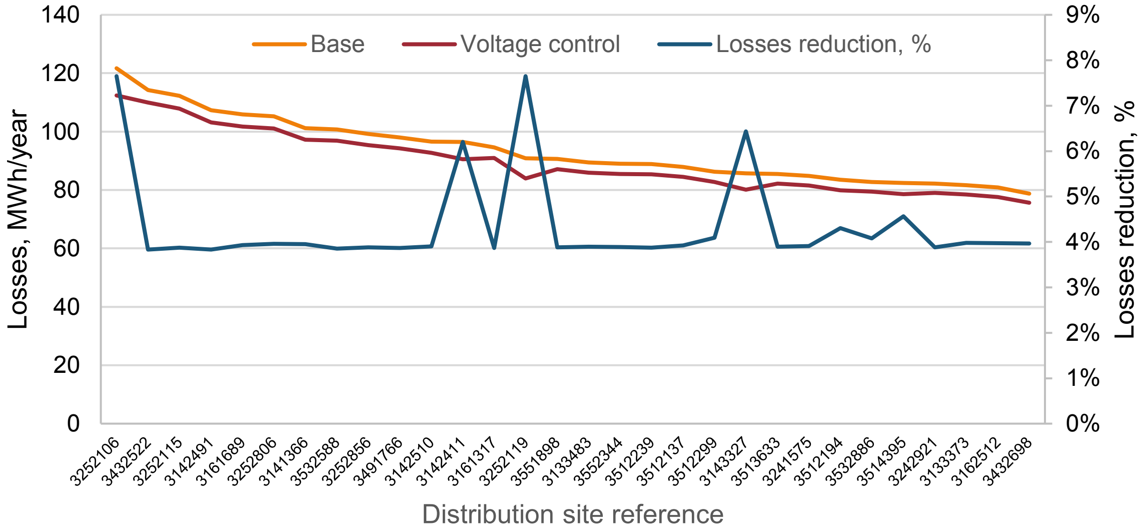



Figure 3.12 The annual EPN LV network losses with and without voltage optimisation and maximum losses reduction in %; sites are ranked by losses reduction in MWh/year; assumed load model is constant impedance

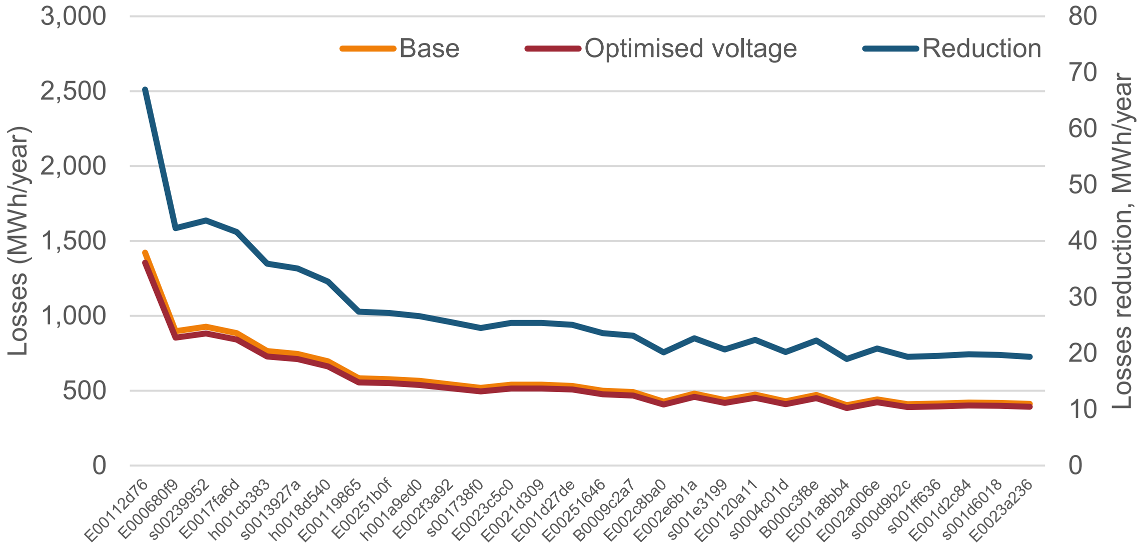



Figure 3.13 List of EPN HV feeders ranked by reduction in losses achieved by voltage control.

The analysis carried out demonstrates that the deployment of voltage control could deliver benefits in terms of losses reduction by exploiting the voltage dependency of certain loads. In the presented studies, these benefits are moderate (around 5%). Given the assumptions related to voltage dependency of demand the capitalised value of losses reduction per each of the identified 30 feeders is between £9.2-15.2k.

## 3.4 Balancing load across phases

In this section, we analyse the impact of balancing the load across different phases on reduction in network losses. As most of end-of-use appliances constitute single phase loads, the loading of different phases can be quite unbalanced, especially in LV networks. The installation of small-scale DG can aggravate the phase imbalance problem. The presence of imbalanced demand increases losses as the flows are not evenly distributed across phases. In addition, load imbalances also trigger current flowing through the neutral conductor which contributes further to losses. The imbalance problem tends to be less pronounced in HV networks due to load diversity; for this reason, this analysis is focused on the LV networks. In this context, modelling has been carried out to investigate the opportunities for loss reduction by improving the load distribution across three phases through optimisation of transformation points, e.g. modern power electronic-based voltage regulators which can be combined with the application of power factor compensation and phase balancing.

The study was carried out on actual UKPN LV networks; the length of the LV circuits considered in this study is given in Table 7 below.

Table 7 Length of installed LV network

| Length ('000 km) | EPN | LPN | SPN | Total |
|---|---|---|---|---|
| LV Cable | 133 | 37 | 55 | 225 |
| LV Overhead Line | 90 | | 57 | 146 |
| Total | **222** | **37** | **111** | **371** |

Losses in LV networks have been quantified under three scenarios: (i) balanced load, (ii) 10% imbalance load and (iii) 30% imbalance load. The load flows and losses for each scenario are recorded and analysed. The results are presented in Figure 3.14.

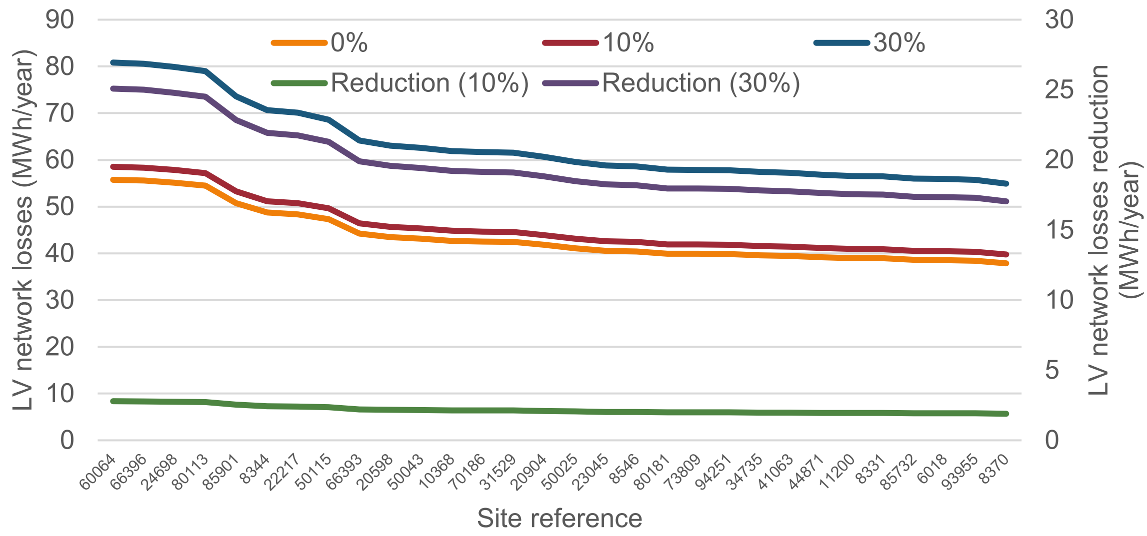



Figure 3.14. Impact of load balancing on the LPN LV network losses.

The x-axis shows the LV sites IDs (sorted from high to low losses sites). The left y-axis presents the annual network losses for the three scenarios, while the right y-axis shows the achieved losses reduction by correcting a 10% and 30% imbalance. The results indicate that the benefits of such correction are up to 5% (=2.8/55.7) and 45% (=25.0/55.7) respectively, highlighting the importance of this strategy in reducing losses. The minimum value of losses reduction per site LV network shown in Figure 3.14 is between £90-£1,360 per year. Further analysis is required to understand in-depth the actual level of imbalance in the UKPN network through suitable measurements and consequently identify priority areas to deploy this strategy.

## 3.5 Harmonics

### 3.5.1 Impact of harmonics on transformer's and Joule losses

The increased penetration of load appliances and DG with power electronics in the distribution network tends to increase generated harmonics. The resulting presence of multiple frequencies will increase heating in the equipment and conductors as well as power quality problems. In this context, we analyse the impact of increased voltage harmonics on losses, particularly on transformer (iron) no-load losses and thermal losses. The impact of total harmonic distortion (THD) on losses is illustrated in Figure 3.15.

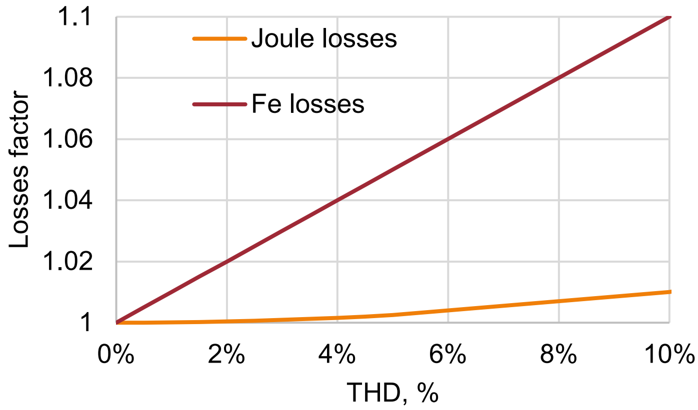



Figure 3.15. Impact of THD on Fe and Joule losses

The graph shows that increased THD increased transformer no-load losses linearly. For example, 10% THD will cause losses to increase by 10%. THD also increases the Joule losses to a lower extent and in a non-linear fashion. Therefore, it would be beneficial to keep the THD in the system as low as possible.

According to the current standards, the maximum limit of THD at distribution transformer is 5% for distribution transformers, 4% for primary substations and 3% for EHV networks[11]. This means that the increase in joule losses is already capped to be modest (<0.2%), but there is a significant opportunity for reducing the Fe losses. A possible strategy is to use transformers with low non-load losses. Another strategy lies in installing filters that can reduce harmonics in the system, e.g. technologies such as powerPerfector, which would optimise voltage and simultaneously reduce harmonics.

### 3.5.2 LV Network Harmonics

The insights from section 3.5.1 motivate an estimation of the impact of filtering harmonics on the losses of selected UKPN LV sites which are shown on the x-axis of Figure 3.16 and are ranked based on the annual losses (from high to low). Two cases are illustrated in the graph: (i) network losses based on the assumption that there are no harmonics (expressed by the orange line) and (ii) losses assuming 10% THD (expressed by the blue line). The green line expressed losses reduction achieved by filtering harmonics. It should be noted that this study considers only the thermal losses in LV network circuits.

[11] ENA ER G5, Energy Network Association Engineering Recommendation (ENA ER): Planning Levels For Harmonic Voltage Distortion

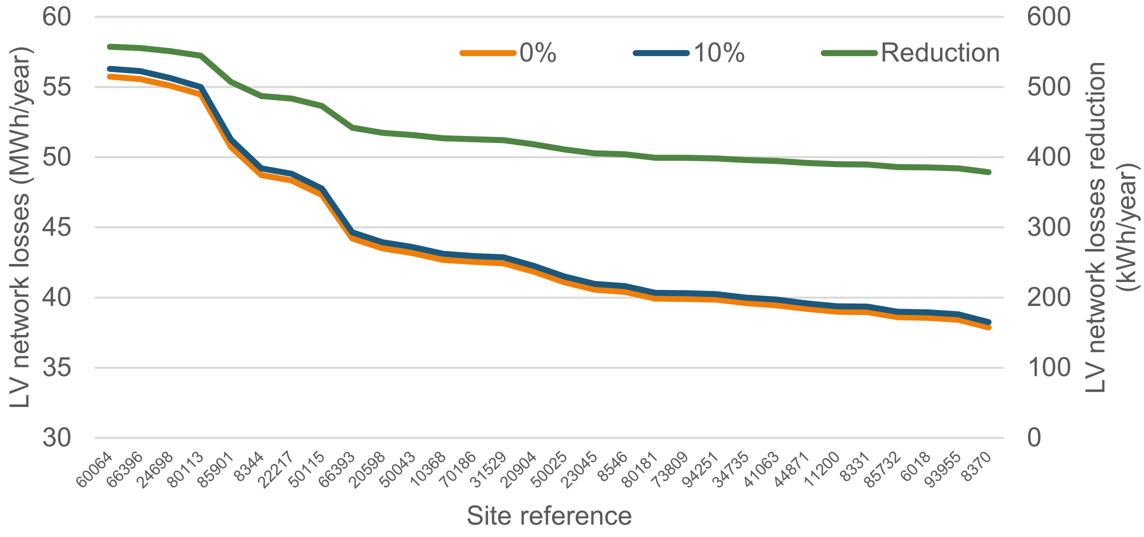



Figure 3.16. Impact of reducing total harmonic current distortion on losses at LV networks.

The results of the study indicate that improving the THD can offer a modest reduction of losses of around 1%. The equivalent capitalised value of improving THD per each site LV network is between £200-300.

### 3.5.3 Long HV Feeders, Harmonic Resonance

Harmonic resonance appears in the electricity network when the natural frequency coincides with the frequency of harmonic current. As the network contains ferrous components that are magnetically energised, the network itself can be the source of harmonics, which increase losses. In this study, we estimate the resonant frequency for different HV cable types (1-core and 3-core), lengths (5 to 30 km), and cross-sectional areas (70 - 630 mm$^2$).

For this study, we use data for Prysmian 11 kV 1-core and 3-core cables and assume a lumped-capacitance cable model. The estimated resonant frequencies for different lengths and diameters of these cables are presented in Table 8 and Table 9 for 1-core and 3-core cables respectively. It shows that the resonant frequency is lower for longer cables and greater cross-sectional areas.

Table 8 Approximate resonant frequency for different lengths and cross-sections (Prysmian 11 kV 1-core).

| CSA | Reactance at 50 Hz, milliohms/km | Maximum capacitance, nanofarad/km | Approximate resonant frequency, Hz, for different cable lengths, km | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 5 | 10 | 15 | 20 | 25 | 30 |
| 70 | 130 | 288 | 2,916 | 1,458 | 972 | 729 | 583 | 486 |
| 95 | 123 | 323 | 2,831 | 1,415 | 944 | 708 | 566 | 472 |
| 120 | 118 | 353 | 2,764 | 1,382 | 921 | 691 | 553 | 461 |
| 150 | 117 | 380 | 2,676 | 1,338 | 892 | 669 | 535 | 446 |
| 185 | 112 | 416 | 2,614 | 1,307 | 871 | 653 | 523 | 436 |
| 240 | 109 | 460 | 2,520 | 1,260 | 840 | 630 | 504 | 420 |
| 300 | 105 | 506 | 2,448 | 1,224 | 816 | 612 | 490 | 408 |
| 400 | 101 | 561 | 2,370 | 1,185 | 790 | 593 | 474 | 395 |
| 500 | 99.8 | 619 | 2,270 | 1,135 | 757 | 567 | 454 | 378 |
| 630 | 96.1 | 697 | 2,180 | 1,090 | 727 | 545 | 436 | 363 |

Table 9 Approximate resonant frequency for different lengths and cross-sections (Prysmian 11 kV 3-core)

| CSA | Reactance at 50 Hz, milliohms/km | Maximum capacitance, nanofarad/km | Approximate resonant frequency, Hz, for different cable lengths, km | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | **5** | **10** | **15** | **20** | **25** | **30** |
| 70 | 108 | 298 | 3,145 | 1,572 | 1,048 | 786 | 629 | 524 |
| 95 | 102 | 334 | 3,057 | 1,528 | 1,019 | 764 | 611 | 509 |
| 120 | 98.8 | 365 | 2,971 | 1,485 | 990 | 743 | 594 | 495 |
| 150 | 96.2 | 392 | 2,905 | 1,453 | 968 | 726 | 581 | 484 |
| 185 | 93.1 | 430 | 2,820 | 1,410 | 940 | 705 | 564 | 470 |
| 240 | 90 | 476 | 2,726 | 1,363 | 909 | 681 | 545 | 454 |
| 300 | 87.4 | 524 | 2,636 | 1,318 | 879 | 659 | 527 | 439 |
| 400 | 84.9 | 580 | 2,542 | 1,271 | 847 | 636 | 508 | 424 |

For 15-20 km HV cables, the harmonic resonant frequency might be lower than 700 Hz at which point it is recommended to carry out a detailed harmonic study. This parallel resonance is characterised by low impedance to the flow of harmonic currents at the resonant frequency which contributes to higher losses[12]. Therefore, for a long HV feeder, e.g. network connection to a wind farm, there may be a case for analysing the harmonic resonance.

## 3.6 Upgrading single phase spur to three phase

Another possible strategy to reduce losses lies in upgrading the single-phase spur to a three-phase one. In this section, we demonstrate theoretically that the implementation of this strategy can reduce losses significantly. For the purpose of this study, 95 $mm^2$ Al 11 kV conductor is analysed assuming that the neutral path is characterised by the same resistance as the phase conductor. The losses for the single-phase and three-phase spur are presented in Figure 3.17. It should be noted that the upstream losses reduction due to imbalance and load reduction are not included in the analysis.

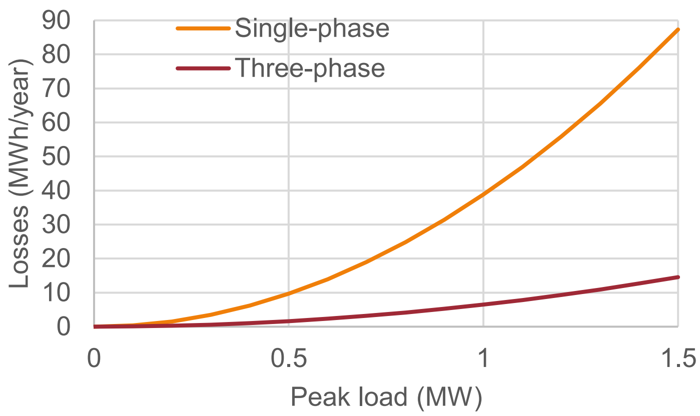



Figure 3.17. Impact of spur upgrading on the LV network losses

Based on the presented results, upgrading the single-phase spur to a three-phase one achieves a very substantial losses reduction of 83%. This is attributed to the fact that after the upgrade more conductors are used to transfer the same energy. However, the cost of such a strategy may be high and therefore its implementation on the spur with high peak demand should be recommended.

[12] UK Power Networks, Business plan (2015 to 2023) Annex 7: Losses Strategy, March 2014

## 3.7 Impact on transmission losses

Implementation of losses reduction strategies at distribution networks will also have impact on the transmission network losses. This impact of course is location-specific, depending on the electrical location of the distribution area in question within the national transmission system. In this context, we have investigated the impact on the losses reduction in the UKPN LPN network on the GB transmission network losses. Due to the geographical location of the UKPN network, i.e. the south of England, and considering that power flows in the transmission network are from north to south, the reduction of losses in LPN distribution network should result in lower losses at the transmission level.

In order to analyse the impacts on transmission losses, the following approach is applied:

1. Marginal losses of the GB transmission network are calculated based on peak demand conditions. The marginal losses are location-specific and indicate the increase in transmission system losses if the demand at the location in question is increased by 1 MW.
2. Based on the results from step 1, the average marginal losses for the GSPs in the LPN area are calculated.
3. Considering the Elexon class 8 profile (with 76% load factor), the potential annual losses reduction in the transmission system is estimated, driven by reduction of losses in LPN's GSP. This analysis suggests that on average, 5.5% reduction in transmission losses can be attributed to the distribution losses reduction in LPN. In other words, 1 MWh reduction in losses in distribution network contributes to 0.055 MWh loss reduction in transmission network.

As losses are a function of system loading conditions, the impact of reduced loading in the LPN network on transmission losses is expected to vary according to the system loading as well. This is illustrated in Figure 3.18.

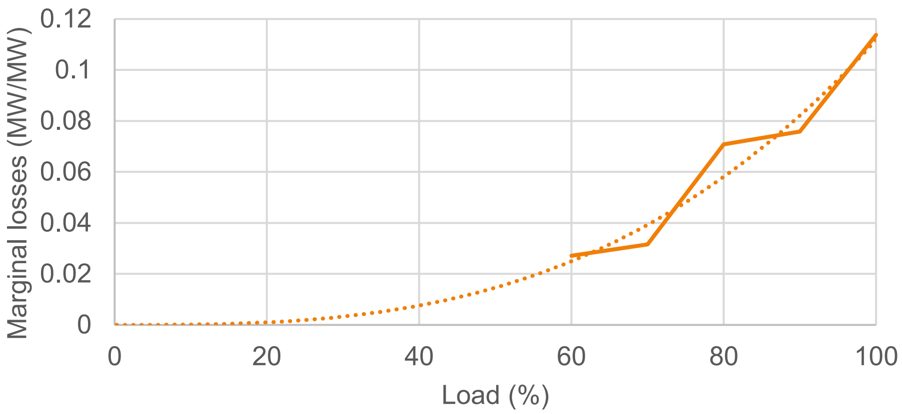



Figure 3.18. Marginal transmission losses corresponding to losses of LPN network as a function of system loading.

For example, during peak load condition (100%), 1 MWh losses reduction in the LPN area would reduce transmission losses by 0.11 MWh. However, when system loading is 60%, 1 MWh losses reduction in the LPN area will reduce transmission losses by 0.024 MWh. This highlights the importance of losses reduction during peak demand conditions.

## 3.8 Matching Demand with PV Output

Demand side management strategies can also yield significant benefits in terms of losses reduction, given that demand flexibility can be used to match DG output and therefore reduce the loading of the network. In this study, we investigate the benefits achieved on UKPN networks by optimising the operation of smart domestic load appliances to match PV output. Elexon Class 1 demand profiles (Table 10), as well as PV output profiles (Figure 3.19) for 15 characteristic days, are used in the analysis.

Table 10. Demand profiles corresponding to 15 characteristic days.

| | Autumn | | | High Summer | | | Summer | | | Spring | | | Winter | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Week Day (WD) | Saturday (Sa) | Sunday (Su) | WD | Sa | Su | WD | Sa | Su | WD | Sa | Su | WD | Sa | Su |
| Index | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |

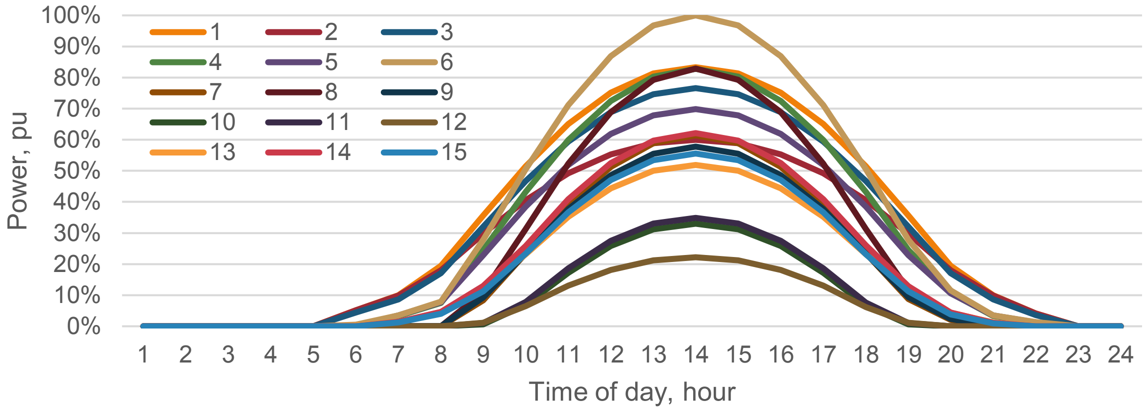



Figure 3.19. PV output profiles corresponding to 15 characteristic days.

Figure 3.20 presents the net demand (demand minus PV output) profiles of the 15 characteristic days considered.

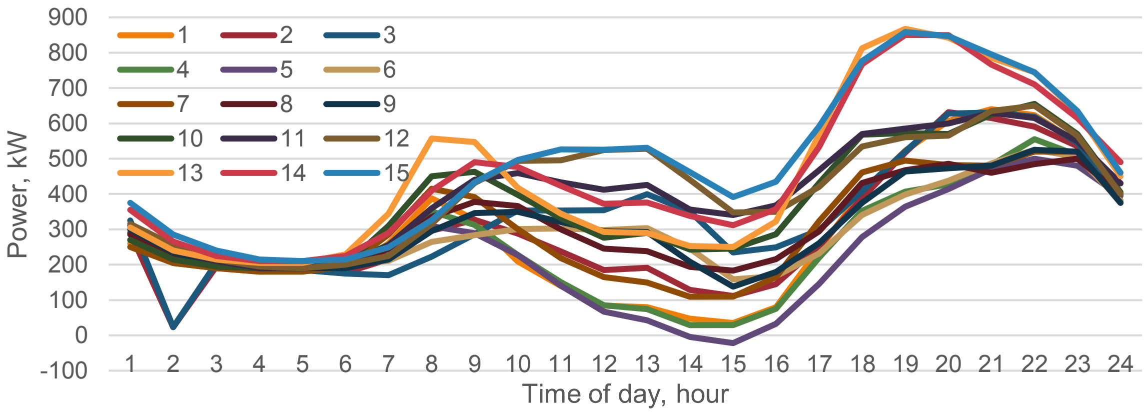



Figure 3.20. Net demand profiles corresponding to 15 characteristic days.

The net demand profiles are modulated by shifting demand of smart appliances from peak to off-peak periods, as shown in Figure 3.21. It can be observed that this demand-side management strategy leads to a reduction of peak demand from about 860 kW to about 760 kW. At the same time, the off-peak load is increased in order to keep the total consumed energy over the day unchanged, satisfying consumers' requirements.

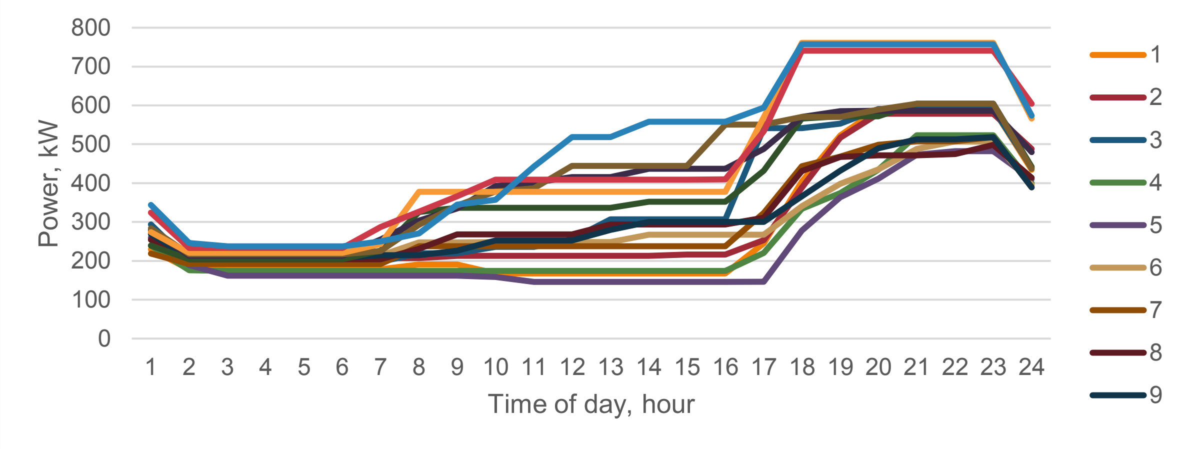



Figure 3.21. Net demand profiles corresponding to 15 characteristic days after demand side management actions.

This change of the net demand profiles results in an overall reduction of network losses of 15% and 40% for a PV penetration of 10% and 20% respectively. This implies that demand-side management actions will have a higher impact on network losses as the PV penetration increases.

## 3.9 Switching off transformers

Switching off primary and grid transformers reduces no-load losses and increases load losses. Hence, if this action is carried out during low loading conditions, there is potential for overall losses reduction, if the reduction in no-load losses outweighs the increase in load losses.

The impact of such a strategy is illustrated on a primary substation containing four EHV/11 kV, 15 MVA transformers. For the purpose of this example, considered load losses are 45 kW, and no-load are losses 30 kW. Furthermore, load profiles for Hyde Park Estate A 11kV (HYPA) substation for the period of 1/2/2013-31/1/2014 are used. The assumed power factor is 0.95.

Breakeven loading for three and four switched on transformers is set at 40.3 MW loading. For two and three it is at 28.5 MW, and for two and one is 16.5 MW loading. This is dependent on the ratio of the load and no-load losses. Hence, if the load is higher than 40.3 MW, transformer losses are the lowest if all four transformers are switched on. If loading is between 28.5 and 40.3 MW transformer losses are lowest if one of the transformers is switched off, and so on.

Figure 3.22 shows the potential for losses reduction depending on the minimum duration of switching off a transformer. If transformers could be switched off and back on again in the next period, potentially 10% of substation losses could be saved. For the one-month minimum duration of the transformer being switched off, about 6% of substation losses could be saved. This is equivalent to £4.9-8.1k cost saving.

However, the potential for savings is highly dependent on the ratio of load to no-load losses. For a typical high ratio (10:1) there is no benefit. Hence, the potential for losses reduction by switching off primary transformers during low demand conditions is very low.

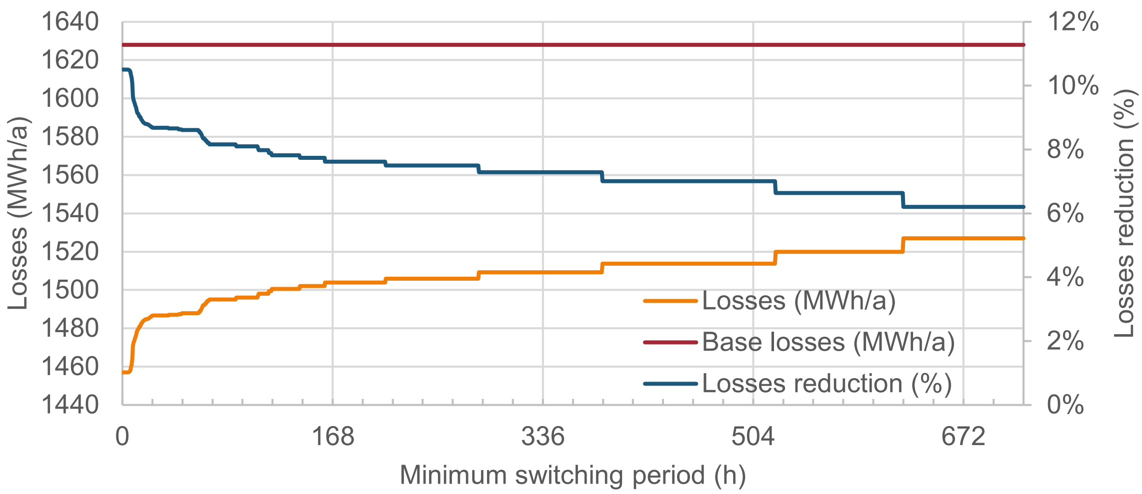



Figure 3.22. Operational diagram assuming minimum switching off period of transformers

## 3.10 Summary

A number of key drivers of network losses have been identified and analysed in order to inform the development of future strategies for reduction of losses. These include changes in network operational topology, improvement of power factor, changes in load profile, management of phase imbalance and harmonics.

Key results of the conducted studies are as follows:

- The analysis aimed at optimising network topology through Normally Open Points (NOP) in the UKPN HV networks, demonstrated that this could result in significant loss reduction in the order of 15%. This concept hence may provide an important opportunity for reducing losses, as the economic case for this method is likely to be strong.
- For the three UK Power Networks licence areas, feeders are ranked by the possible reduction in losses driven by power factor improvement. The potential for loss saving is assessed assuming power factor improvement from 0.85 to 0.95. This led to reduction in losses in each feeder between 20 and 25%. For a single point, PF compensation losses reduction that could be achieved is between 11 and 14%. It is interesting that the analysis demonstrated that improving power factor in only one third of HV feeders could achieve 90% of potential losses reduction. Hence, the list of 30 highest ranked HV feeders is each licence area is created and measurements of the actual power factor in future trials are proposed to be carried out.
- Modelling carried out demonstrated that the impact of imbalance level on losses is nonlinear. Imbalance of 10% and 30% would potentially lead to increase in losses of 5% and 45%, respectively, and hence feeders with high phase imbalance should be identified. List of 30 highest ranked LV networks are identified for further measurements and consideration for reduction of possible load imbalance.
- Given that current harmonics are kept low by design, the impact on network losses and transformer load losses is unlikely to be significant. On the other hand, impact of voltage harmonics on transformer no-load losses is linearly dependant on the total harmonic distortion (THD), and hence impact on losses may be more significant. Given the standard, THD is below 5% at distribution transformer, below 4% at primary substation and below 3% at EHV. On the other hand, given future deployment of Eco design transformers with lower no-load losses, the impact of THD is likely to reduce.

# 4 Application of smart technologies for reduction of losses

**Context: Maximising the Value of Smart Grid for Network Congestion and Losses**

The need to accommodate growing penetration of low carbon technologies (renewable generation, electrification of heat and transport sectors) has challenged the traditional operation and design paradigm of distribution networks. Therehave been very significant innovation activities aimed at enhancing utilisation of existing infrastructure in order to reduce network reinforcement needs. A range of smart-grid technologies and systems (e.g. active network control, energy storage, demand side response, dynamic line rating etc.) has been successfully applied in enhancing network asset utilisation, whichgenerally leads to an increase in network losses. Analysis demonstrates that the increase in network losses driven by the application of smart-grid technologies is economically justified, as savings in network reinforcement costs outweigh the additional losses of the smart grid paradigm.

On the other hand, some of these smart grid technologies and systems could also potentially be applied to reduce losses, in addition to deferring network reinforcement and facilitating larger penetration of low carbon technologies. In this context, analyses have been carried out to assess the potential opportunities offered by smart grid technologies to reduce network losses, with particular focus on existing solutions that have been trialled by UK Power Networks to facilitate connection of low carbon technologies.

## 4.1 Case Study No 1 - Flexible Plug and Play (FPP) Project

In this work, we investigate the opportunity of using the Quadrature Booster (QB) to minimise network losses. The QB was deployed in the Flexible Plug and Play (FPP) project to manage load flows on congested circuits. The FPP was a Second Tier Low Carbon Network Fund (LCNF) project aimed at trialling new technologies and novel commercial solutions to achieve cost-effective integration of distributed generation (DG), such as wind power or solar, into the electricity distribution network. The QB has been deployed to relieve the network constraint in the Wissington area. The system is presented in Figure 4.1.

Due to the thermal limit constraint on the 2nd circuit, the output of CHP at Wissington would need to be constrained (especially during low demand conditions). Instead of reinforcing the circuit, a QB was installed to enhance utilisation of the spare capacity on the adjacent circuit (shown in the diagram) which otherwise could not be used without the QB (due to its high impedance characteristic). By managing the flows on these two circuits, it is demonstrated that the QB can defer network reinforcements and allow higher utilisation of the CHP plant at Wissington.

In this context, the QB is controlled such that the flows are divided evenly between the 1st and 2nd circuit. While this approach solves the network congestion issue; this may lead to higher losses since the impedance of the 1st circuit is high, and therefore, it is not recommended to always increase the flows at the 1st circuit.

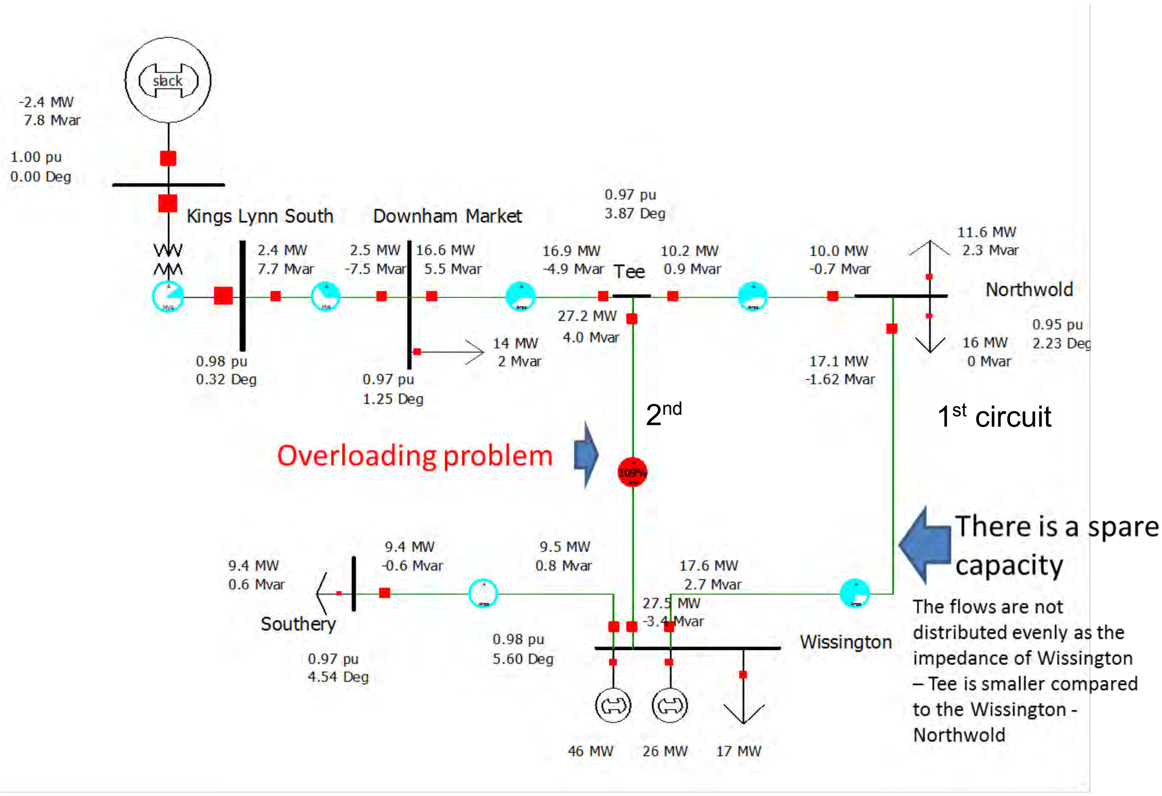



Figure 4.1 Wissington test system

In the next section, we will analyse a different control approach for the QB that leads to smaller losses.

### 4.1.1 Loss performance of different control approaches for QB

There are two control approaches that have been analysed:

1. Balancing the flows: in this approach, QB is used to balance the flows in the 1st and 2nd circuit at all times. The control algorithm is relatively simple as it only needs to monitor the flows at both circuits and adjust the setting of the QB to balance the loading of the two circuits.
2. Minimising the losses: in this approach, the QB is used to manage the thermal loading but also network losses. In order to optimise the setting, a Security Constrained Optimal Power Flow (SCOPF) model based on the real-time system operating conditions is applied. The impact of the flows in the broader system can be analysed and computed to achieve the optimal results from the overall system perspective. While this requires a more complex control algorithm, this approach would deliver more optimal losses performance.

The results of these approaches are shown in Table 11. The results demonstrate that the losses in the scenario where the QB is controlled only to balance the line loading, the losses are higher by 11% - 25% compared to the losses if the QB is optimised concurrently to minimise the losses.

Table 11 Performance of different QB control approaches on losses

| *System conditions* | Losses per hour (MWh) | | Loss reduction |
|---|---|---|---|
| | Balancing line loading | Flow management with minimisation of losses | |
| **High demand – high DG** | **1.7** | **1.5** | **11%** |
| **Low demand – low DG** | **2** | **1.5** | **25%** |

This finding suggests that there is a significant opportunity to reduce network losses by optimising the settings of QB for losses management, in addition to managing constraints and voltage violations. This analysis suggests that the QB could be used to increase the flows in the low-losses circuit (2nd circuit) – up to its thermal limit, rather than balancing the load between both circuits, as the impedance of the 1st circuit is three times the impedance of the 2nd circuit. This is shown in Figure 4.2.

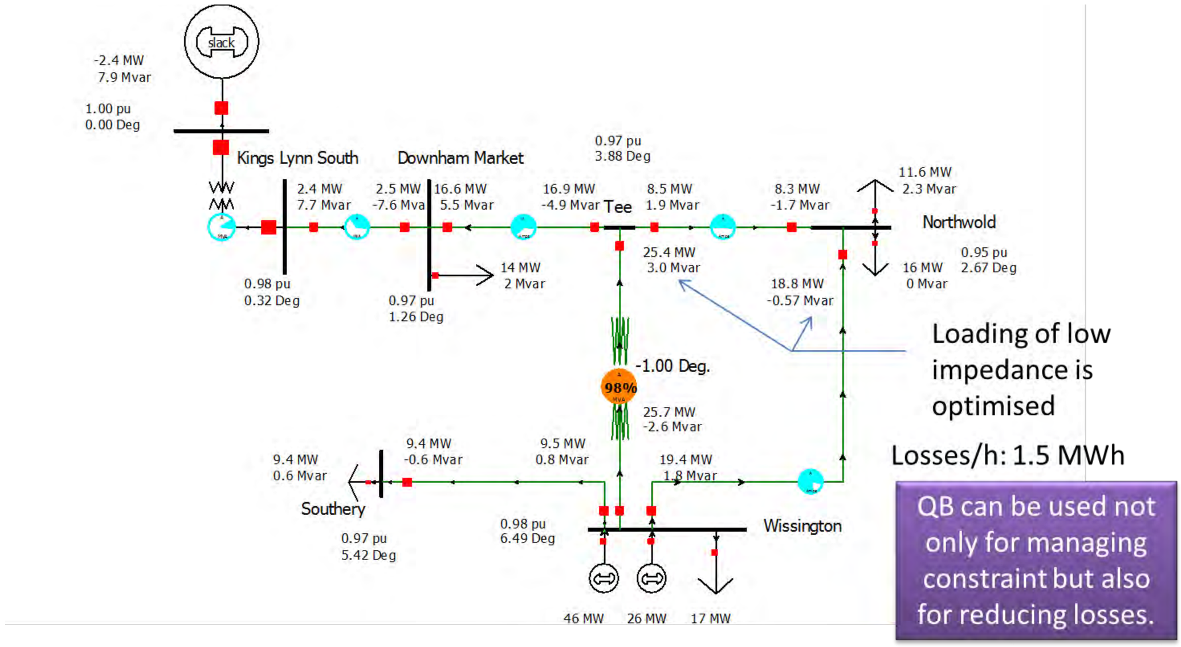



Figure 4.2 QB is used to manage the flow and losses

Optimising the setting of QB for management of losses requires detailed understanding of the network impedance characteristics and may not be straightforward; hence, advanced network optimisation tools, such as SCOPF, would be needed to support the system operator in determining the optimal QB setting while respecting the network constraints (voltages and thermal limits).

In summary, more value can be extracted from smart grid technologies like the QB if it could be used to simultaneously manage network congestion and also to reduce losses. In this study, the losses could be reduced by 11% to 25%, which are attractive opportunities to be explored. However, it requires significantly more complex control algorithms and the cost implications of this strategy need to be investigated. For example, costs resulting from more frequent changes to the QB settings.

### 4.1.2 Distributed Generation (DG) reactive power capability for losses reduction

Traditionally, DG operates at unity power factor. This is achieved by internal compensation of the DG's reactive load. This control approach is practical for the passive distribution network as the distribution system operator/planner would not need to consider the impact of DG's reactive load on the system. However, when the system voltages, flows, and losses are being managed more actively, there may be significant opportunity to apply this "hidden" reactive capability to manage the voltages and losses in the system.

In this context, a set of studies have been carried out analysing the benefits of controlling DG's reactive power capability to reduce network losses. For this purpose the 33 kV EPN distribution system between Peterborough and March is analysed, see Figure 4.3. This is the FPP trial zone which serves an area of approx. 30 km diameter (700 km$^2$) and is particularly well suited for renewable generation. Over recent years UK Power Networks have actively facilitated significant growth in connection applications and corresponding deployment of renewable generation in this area. More than 230 MW of DG have been already connected and it is expected to increase further in future. The system used for the study is shown below.

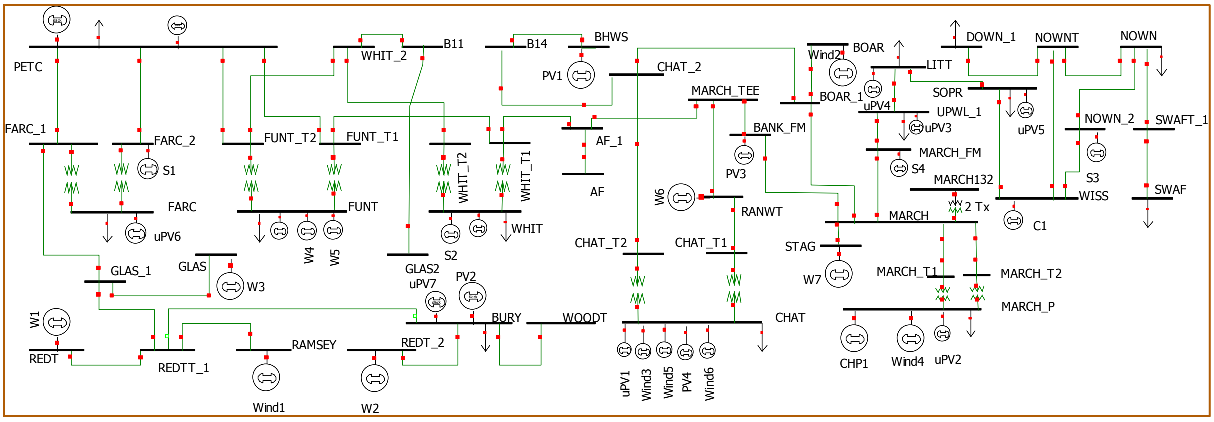



Figure 4.3 Flexible Plug and Play network

For this analysis, we evaluate the impact of DG's reactive power on the system losses across a set of operating conditions considering the variation in demand and the output of variable generators (wind, PV) across one-year period. The study varies the DG's reactive power capability between 0.75 (lag/lead) and unity power factor. DG's reactive power output is optimised using the Optimal Power Flow (OPF) algorithm to minimise the total operation cost of the system including the cost of curtailing DG and losses. The impact of having different reactive power capability on losses are shown in Figure 4.4.

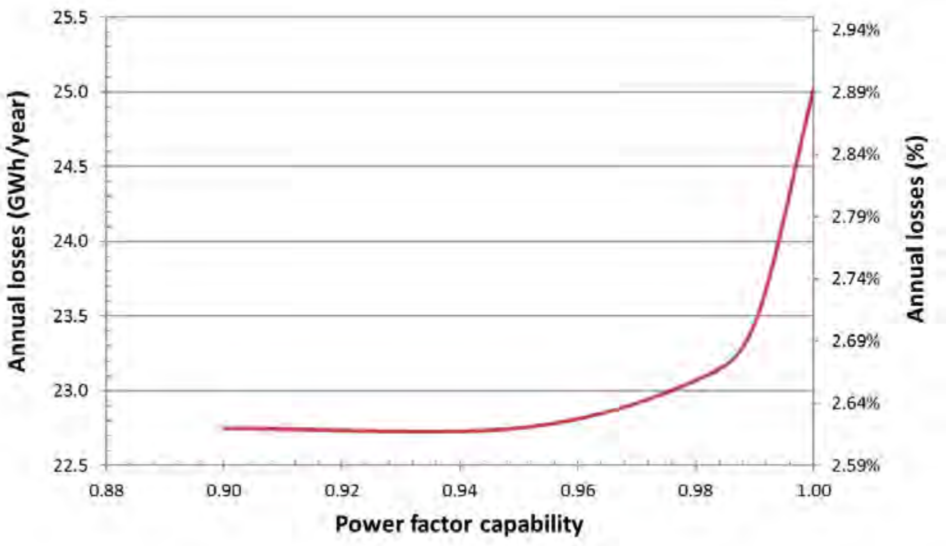



Figure 4.4 Benefits of controlling DG's reactive power capability on losses

The results demonstrate that by controlling DG's reactive power capability via active network management, the volume of DG curtailment can be reduced from 2.4% to 0.2% and the losses also decrease from 2.9% to 2.6% (a reduction of about 10%). This is expected since the reactive power from DG can be used to control system voltages and relieve the voltage-driven network constraints, which may cause DG curtailment. Modelling demonstrates that in this particular case there is a trade-off between cost of losses and cost of DG curtailment.

This analysis also suggests that the value of the first available reactive capacity is higher than subsequent capacity. This is demonstrated in Figure 4.4 where the losses are reduced sharply when DG is able to operate beyond the unity power factor. However, the reduction in losses starts to saturate at 0.95 pf. Increasing the reactive capability further does not reduce the losses further.

These results provide some new insight related to the efficient level of DG reactive capability needed by the system, and this can inform the design or sizing of the DG's reactive power support. It is important to note that the impact on losses in the study is limited within the perimeter of the test system. Furthermore, there may be additional losses reduction obtained in the upper voltage network but this is expected to be marginal.

As the impact of reactive power tends to be local, the value of reactive power services tends to be very locational and system specific as well. In this context, to illustrate the point, we have analysed the utilisation of DG reactive power across all operating conditions. The results are shown in Figure 4.5.

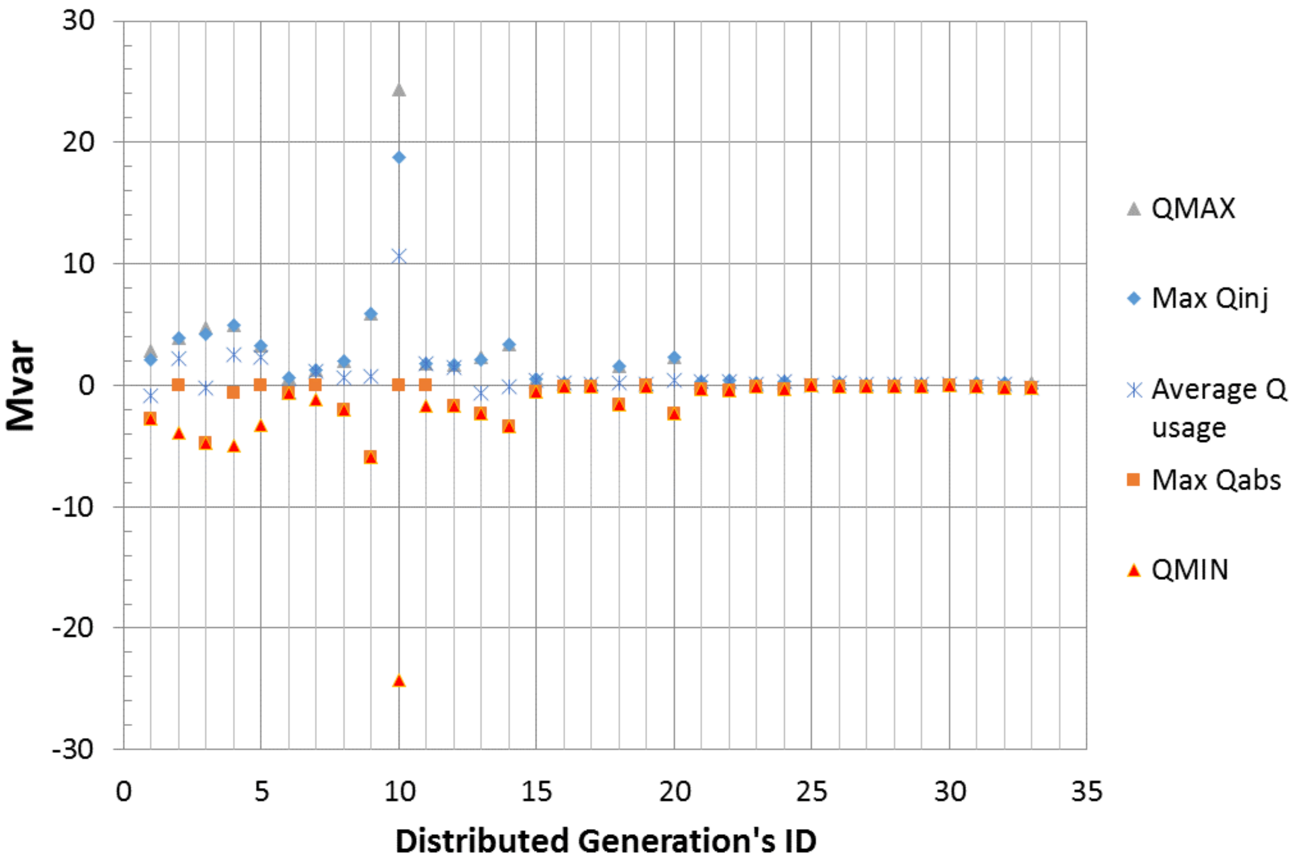



Figure 4.5 Utilisation of reactive sources

The results show the limit for injecting (QMAX) and absorbing (QMIN) reactive power, the maximum reactive power injection (Max Qinj) and absorption (Max Qabs), and the average reactive power usage (Average Q usage). It is shown in Figure 4.5 that not all of the capacity available (injection or absorption) is used by the system. For example: DG with ID=10 should only provide capability to inject reactive power, while for DG with ID=9, should be able to operate with leading or lagging power factor. This type of analysis is important for identifying the requirement for local reactive power services; in the future, this service may have commercial value which would incentivise the provision of such services to reduce network losses.

In conclusion, the ability to utilise DG's reactive power capability by controlling its reactive output according to the system needs can contribute to a reduction in network losses in addition to relieving voltage-driven network constraints that may trigger DG curtailment and increase the need for network reinforcement. While the potential losses reduction is system specific, this study shows around 10% improvement in losses could be achieved. The study also shows that enabling DG to operate with 0.95 pf may be desirable; the benefit of increasing further the reactive capability in terms of losses reduction is small.  This analysis also demonstrates that the value of reactive power services is location specific.

## 4.2 Case study No 2: Soft open points for loss minimisation

### 4.2.1 Introduction

The overarching aim of the Flexible Urban Networks at Low Voltage (FUN-LV) project was to explore the use of power electronics devices (PEDs) to enable deferral of reinforcement and facilitate the connection of low carbon technologies and distributed generation in urban areas. This was to be achieved by meshing existing networks which are not currently meshed, and by removing boundaries within existing meshed networks. In this section, we evaluate the potential for soft open points (SOPs) in reducing losses through balancing loading among distribution substations..

A non-linear optimisation model was developed to simulate system operation. The model's objective function was the minimization of losses while a DC power flow formulation was adopted throughout this analysis.

Using three case studies, based on data provided by UK Power Networks, this analysis demonstrates that the potential for loss minimisation can be substantial, yet it depends highly on network loading and the efficiency of the SOP devices. In particular, whereas fully efficient SOPs are shown to lead to energy loss reductions in the range of 10%, the benefit of less efficient SOPs may be severely limited.

### 4.2.2 Case Study 1: Eastbourne Terrace

We evaluate the potential for a 240kW dual-terminal soft open point to minimize transformer losses in the area of Eastbourne Terrace; The SOP is assumed to be fully efficient. The network diagram and corresponding demand profiles are shown in Figure 4.6 below. We have isolated two substations for analysis; West Terrace and East Terrace. West Terrace has a 750kW transformer and a peak demand of 440 kW. East Terrace has a 500kW transformer and a peak demand of 290 kW. In terms of transformer load losses, these were estimated at 10kW at full loading for West Terrace and 6.68kW at full loading for East Terrace.

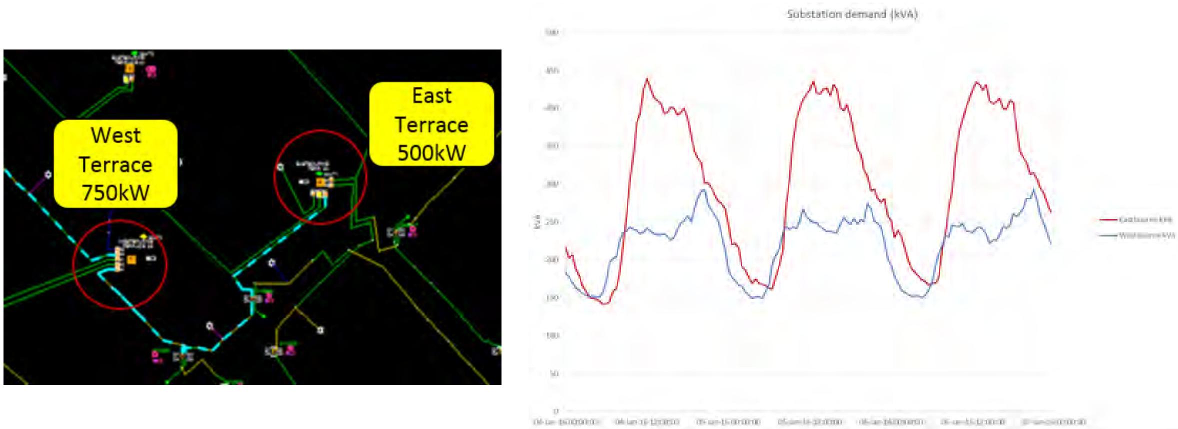



Figure 4.6: Eastbourne Terrace network (left panel) and typical demand profiles (right panel).

Network operation with and without SOP for one typical day is shown in Figure 4.7 below. As can be seen on the left, in the base case without SOP, East Terrace is more loaded than West Terrace. This provides potential for re-balancing between the two transformers. Average losses over a typical day were found to be 83.37kWh. With the installation of an SOP the losses were reduced to 71.08kWh i.e. a 14.7% reduction. As shown in the right panel of Figure 4.7, this is achieved by increasing the loading of the West Terrace and then transferring this excess energy back to East Terrace via the SOP.

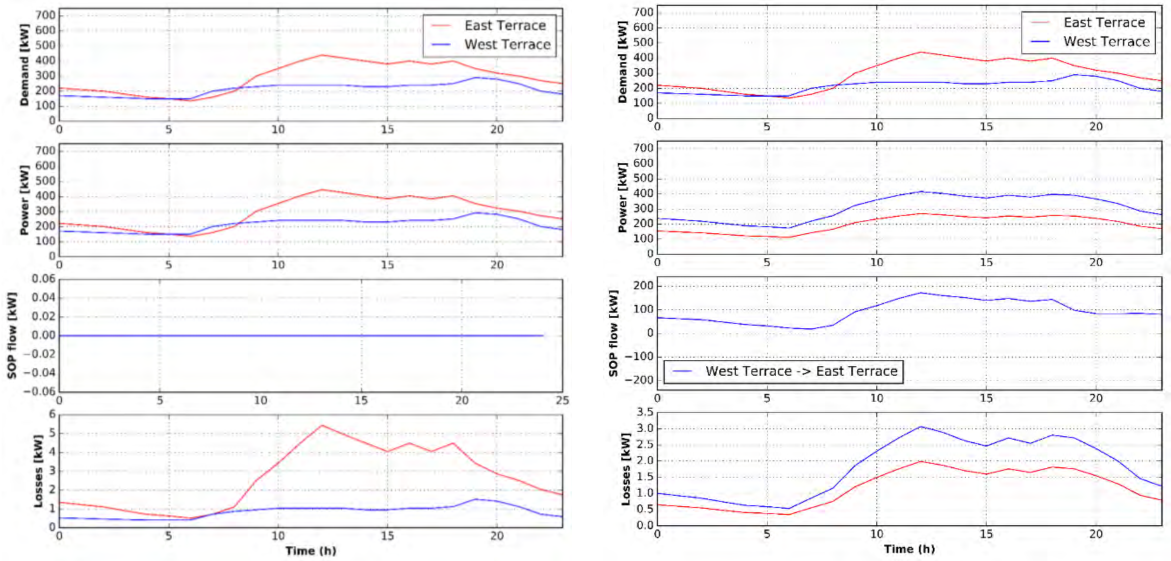


Figure 4.7: Network operation for a typical day without SOP (left panel) and with SOP (right panel).

### 4.2.3 Case Study 2: Boyce's Street

We evaluate the potential for a 240kW dual-terminal soft open point to minimize transformer losses in the area of Boyce's Street. The network diagram and corresponding demand profiles are shown in Figure 4.8 below. Two substations are considered in this analysis; West Terrace and East Terrace. Churchill Square has a 1000kW transformer and a peak demand of 800kW. Duke Street has a 1000kW transformer and a peak demand of 350 kW. In terms of transformer losses, these were estimated at 11.8kW for full loading for both Churchill Square and Duke Street transformers.

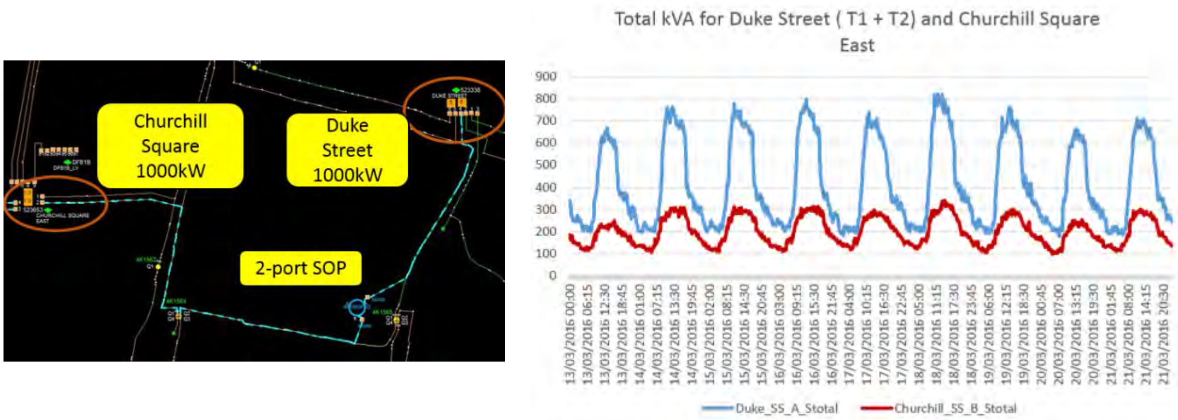



Figure 4.8: Boyce's Street network (left panel) and typical demand (right panel).

Network operation with and without SOP for one typical day is shown in Figure 4.9 below. As can be seen on the left, in the base case without SOP, Duke Street is more loaded than West Terrace providing potential for demand re-balancing between the two substations. Average losses over a typical day were found to be 80.17kWh. With the installation of an SOP the losses were reduced to 70.89kWh. The SOP was able to achieve 11.5% reduction by increasing the loading of Churchill Square, particularly during midday and afternoon hours. Note that as shown in the second plot of the right panel, the SOP reaches its maximum rating of 240kW at around 1pm and thus this particular network would benefit from a larger SOP.

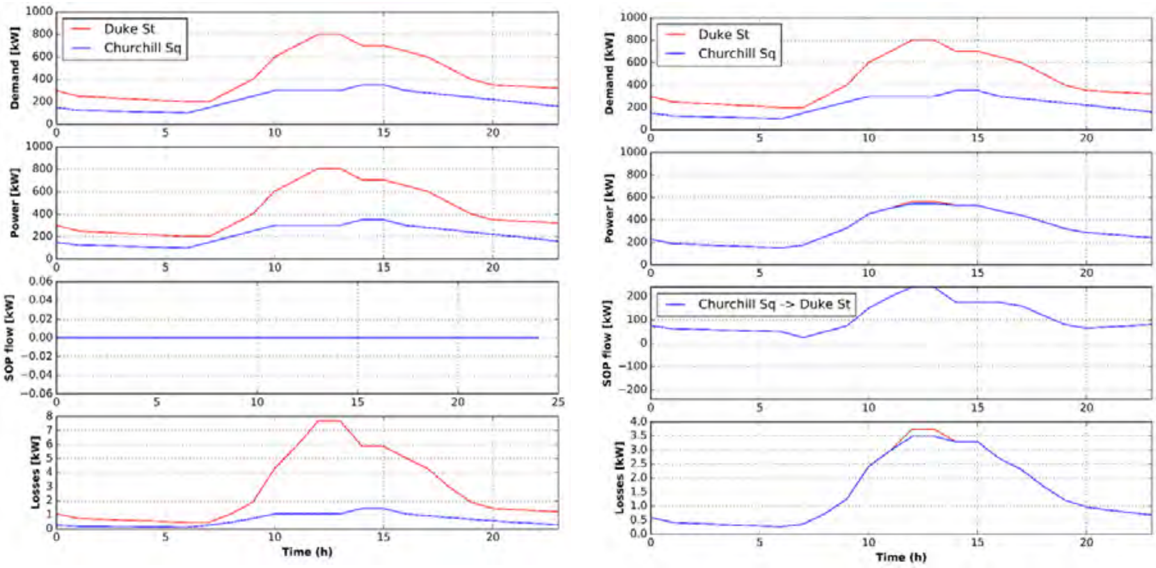



Figure 4.9: Network operation for a typical day without SOP (left panel) and with SOP (right panel).

### 4.2.4 Case Study 3: Prudential North

We carry out a similar analysis on the Prudential North network to evaluate the potential for a 400kW multi-terminal soft open pint to minimize transformer losses. The network diagram and corresponding demand profiles are shown in Figure 4.10 below. We have focused on three substations for analysis; Vokins, Prudential North and New Road. Prudential North and New Road have 1000kW transformers and a peak demand of 390 and 600 kW respectively. Vokins has an 800kW transformer and a peak demand of 160 kW. In terms of transformer losses, these were estimated at 11.8kW and 10.0kW at full loading for the large and smaller transformers respectively.


Figure 4.10: Prudential North network (left panel) and typical demand profiles (right panel).

Network operation with and without SOP for one typical day is shown in Figure 4.11 below. As can be seen on the left, in the base case without SOP, New Road is more loaded than Vokins and Prudential North, providing potential for re-balancing between the three substations. Average losses over a typical day were found to be 74.97kWh. With the installation of a three-port SOP the losses were reduced to 65.50kWh i.e. a 12.6% reduction. As shown in the right panel of Figure 4.11, this is achieved by transferring energy via the SOP from Vokins to Prudential North and from Prudential North to New Road, resulting in increasing the loading of Vokins and decreasing losses in the other two substations.

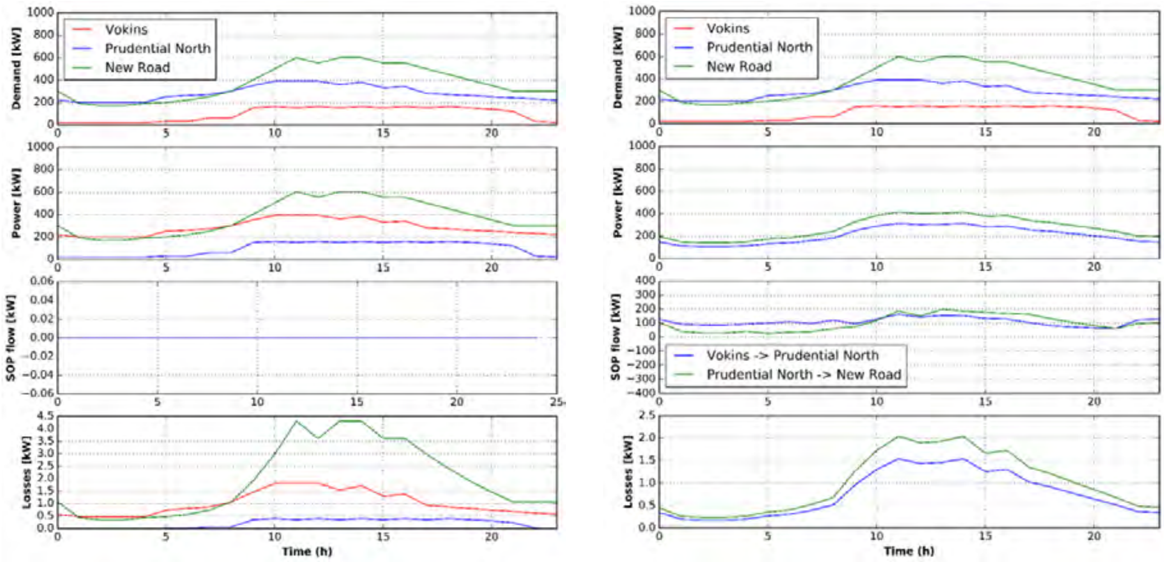


Figure 4.11: Network operation for a typical day without SOP (left panel) and with SOP (right panel).

### 4.2.5 Impact of SOP efficiency

The preceding analysis has assumed 100% efficiency for the SOPs. When performing the three case studies under the assumption of a 90% efficient SOP, the benefits were found to be considerably reduced. In particular, in the case of Eastbourne Terrace and Boyce's Street, the SOP could not assist in loss reduction while in the case of Prudential North, average daily losses were reduced by 3.3%. Results of the three case studies are summarised in Table 12.

Table 12: Summary of results – percentage off loss reduction per case study.

| Case Study | 100% efficiency | 90% efficiency |
|---|---|---|
| **Eastbourne Terrace** | 14.7% | 0.0% |
| **Boyce's Street** | 11.5% | 0.0% |
| **Prudential North** | 12.6% | 3.3% |

## 4.3 Case study No 3: Role and value of energy storage systems in minimizing distribution network losses

### 4.3.1 Introduction

Energy storage systems can offer a large number of valuable services to current and future low-carbon power systems, including balancing of demand and supply across multiple timescales, and the reduction of peak demand. Energy storage can also enhance the cost efficiency of distribution networks by mitigating thermal and voltage constraints and therefore avoiding the capital intensive reinforcement of distribution assets. This is primarily achieved by reducing peak demand levels and shifting demand to adjacent off-peak periods. However, this also creates a value stream of storage which has not been fully appreciated and involves the reduction of network losses and the associated societal costs. This can be achieved by suitable coordination of storage active power; but also through the coordination of their reactive power contributions, given the advanced reactive control capabilities of modern inverters.

This section analyses the impacts of different storage operating policies on network losses. In order to achieve that, the interdependencies between the provision of local distribution network services and the participation in nation-wide energy and balancing markets are explored. Finally, the impacts of different operational parameters of storage (including round-trip efficiency, power and energy capacity and reactive power control capabilities) on the overall performance of these services are investigated.

## 4.3.2 Modelling considerations

### *4.3.2.1 Input Data*

The analysis discussed above is carried out on a model of the Leighton Buzzard primary substation, illustrated in Figure 4.12. Detailed data regarding the network parameters in this test network were considered in the executed power flow analysis.

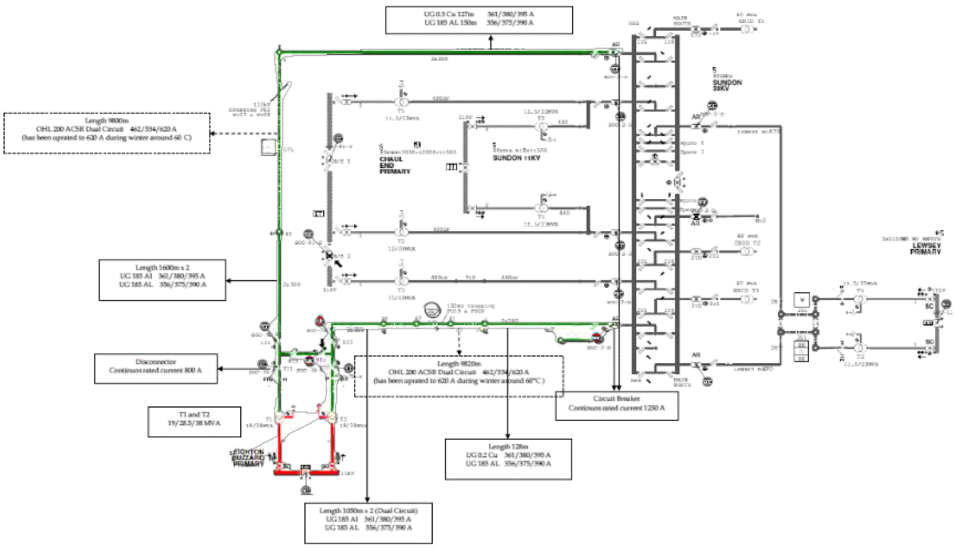
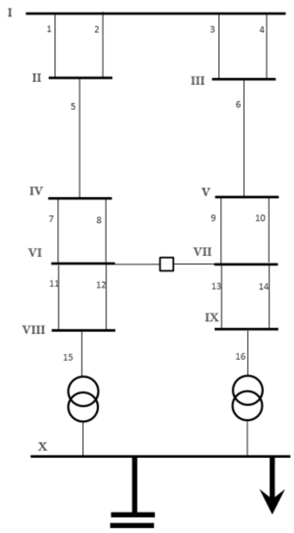



Figure 4.12. Topology of distribution network at Leighton Buzzard substation

The two feeders connected at the Leighton Buzzard substation (indicated in red and green colour in Figure 4.12) are comprised by a number of sections with underground cables and overhead lines. The different sections along with their detailed parameters are presented in Figure 4.13.




| Section ID | Length (km) | Resistance (Ohm/km) | Reactance (Ohm/km) | Capacity (MVA) |
|---|---|---|---|---|
| 1 | 0.15 | 0.165 | 0.101 | 21.4 |
| 2 | 0.13 | 0.093 | 0.101 | 28.0 |
| 3 | 0.13 | 0.140 | 0.109 | 21.7 |
| 4 | 0.13 | 0.165 | 0.101 | 21.4 |
| 5 | 9.84 | 0.137 | 0.326 | 30.5 |
| 6 | 9.82 | 0.137 | 0.326 | 30.5 |
| 7 | 1.63 | 0.165 | 0.101 | 21.4 |
| 8 | 1.64 | 0.165 | 0.101 | 21.4 |
| 9 | 1.02 | 0.165 | 0.101 | 21.4 |
| 10 | 1.06 | 0.165 | 0.101 | 21.4 |
| 11 | 0.64 | 0.148 | 0.347 | 30.5 |
| 12 | 0.64 | 0.148 | 0.347 | 30.5 |
| 13 | 0.64 | 0.148 | 0.347 | 30.5 |
| 14 | 0.64 | 0.148 | 0.347 | 30.5 |

Figure 4.13. Simplified network diagram of Leighton Buzzard primary substation and respective feeder section parameters

The two transformers corresponding to sections 15 and 16 in Figure 4.13 exhibit significant no-load (iron) losses (11.8kW each) generated by magnetizing current at their core and depending on the magnetic properties of the materials in the transformer's core.

Hourly data corresponding to the total demand at the Leighton Buzzard substation and the energy market prices for a typical summer day and a typical winter day are presented in Figure 4.14. The power factor of the demand is assumed equal to 0.9, while the energy market prices have been determined based on 2015 average conditions. The model assumes that the cost of losses for the distribution network operator is determined according to the same energy prices.

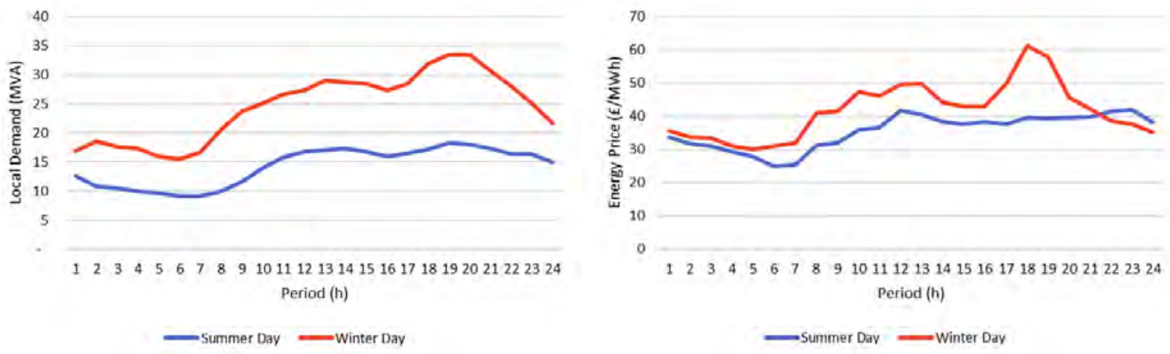



Figure 4.14. Typical profiles of (a) local demand at Leighton Buzzard substation and (b) energy market price

The storage considered in this analysis is assumed to participate both in the energy market to seize arbitrage opportunities (buying energy during periods of low prices and selling energy during periods of high prices) but also in the balancing market through the provision of frequency response services. In this context, typical availability prices for the provision of Firm Frequency Response (FFR) in the UK have been used in the analysis.

The storage operational parameters considered are as follows:

- Active power capacity: 6 MW
- Apparent power capacity: 7.5 MVA
- Energy capacity: 10 MWh
- Round-trip efficiency: 90%

#### 4.3.2.2 Key modelling aspects

The employed modelling approach goes beyond considering provision of individual services by energy storage and investigates a multi-service business framework. In other words, it assumes that storage can simultaneously participate in multiple markets and provide multiple valuable services. In this framework, storage needs to optimally allocate its power and energy capabilities to various services while accounting for the interdependencies and conflicts between these services. More specifically, the model accounts for:

- *Participation in energy market*: storage participates in the day-ahead energy market to seize arbitrage opportunities i.e. buy energy during periods of low prices and sell energy during period of high prices.
- *Provision of frequency response services*: storage participates in the balancing market through the provision of firm frequency response. This requires rapid response times and would be particularly well suited for Li-ion batteries.
- *Provision of network services*: storage is capable of mitigating distribution network constraints during peak demand periods as well as reducing network losses.

In the context of analysing the impact of energy storage operation on network losses, various operating policies have been established focusing on the potential synergic and conflicting actions with other services. Specifically, the following operating policies have been considered:

- ***Base case***: This case serves as a benchmark and assumes that energy storage is not available in the network. Therefore, the model determines the network losses associated with meeting the local demand without storage.
- ***Min Losses***: This operating policy prioritises the reduction of network losses and thus optimises the operation of storage to minimise network losses. Therefore, storage effectively disregards the market signals from energy and balancing markets when optimising its actions.
- ***Max Profit***: This operating policy prioritises the participation of storage in energy and balancing markets and thus optimises the operation of storage to maximise its revenue from these markets. Therefore, storage effectively disregards the impact of its actions on network losses.
- ***Optimized***: This operating policy reconciles the conflicts between the previous two policies by maximising the difference between the revenue of storage in energy and balancing markets minus the energy cost of network losses.

### 4.3.3 Results

Figure 4.15 presents the net demand profiles (combination of local demand and energy storage actions) as well as the energy storage output corresponding to the *Base Case* and *Min Losses* operating policies in a typical winter day. Application of the *Min Losses* operating policy leads to a reduction of peak demand (between hours 17 and 22) and shift of demand towards off-peak periods (between hours 1 and 7).

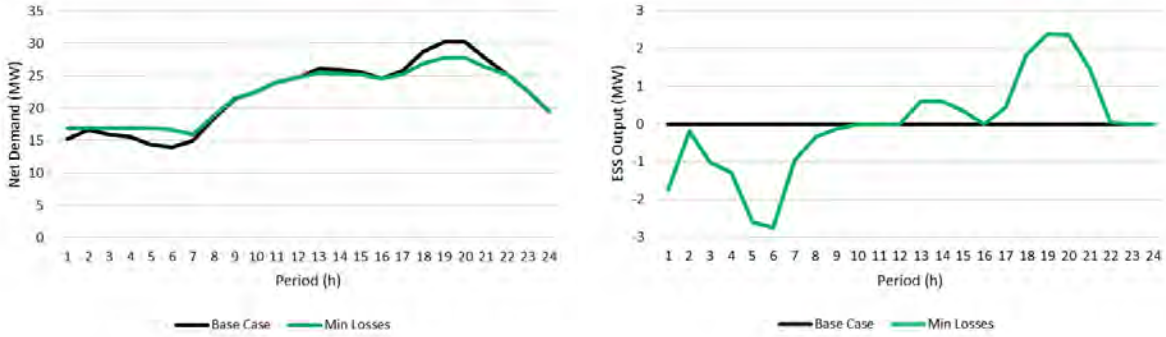



Figure 4.15. a) Net demand and (b) storage output corresponding to the Base Case and Min Losses operating policies

Figure 4.16 illustrates the reduction in network losses achieved with the *Min Losses* policy in comparison to the *Base Case*.

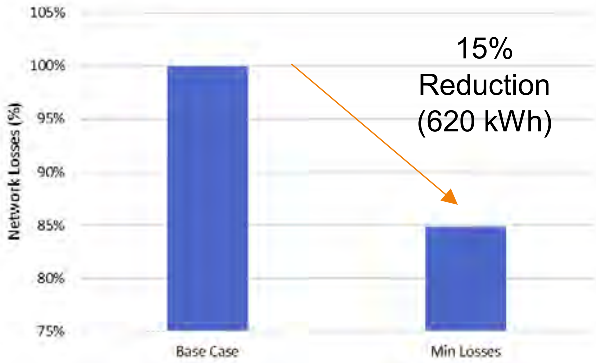



Figure 4.16. Network losses corresponding to the Base Case and Min Losses operating policies

Furthermore, by analysing the load duration curve over 1 year of operation for both *Base Case* and *Min Losses* operating policies (Figure 4.17), it becomes clear that the latter policy reduces local peak demand. The above results demonstrate that reducing network losses is synergic with the reduction of peak demand levels and the avoidance of network reinforcements.

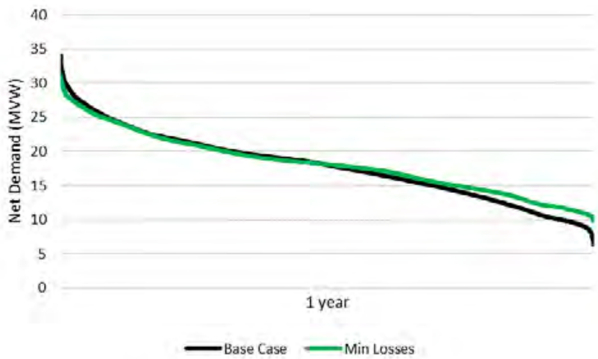



Figure 4.17. Load duration curve corresponding to Base Case and Min Losses operating policies

Going further, Figure 4.18 presents the net demand profiles and the network losses corresponding to the *Base Case*, *Min Losses* and *Max Profit* operating policies. Although the *Max Profit* policy disregards the impact of storage actions on network losses, it leads to lower losses with respect to the *Base Case*. This is driven by the fact that energy market prices and local demand are often correlated, i.e. they exhibit coincident peaks and valleys. However, the reduction of losses is not as significant as in the case of the *Min Losses* policy.

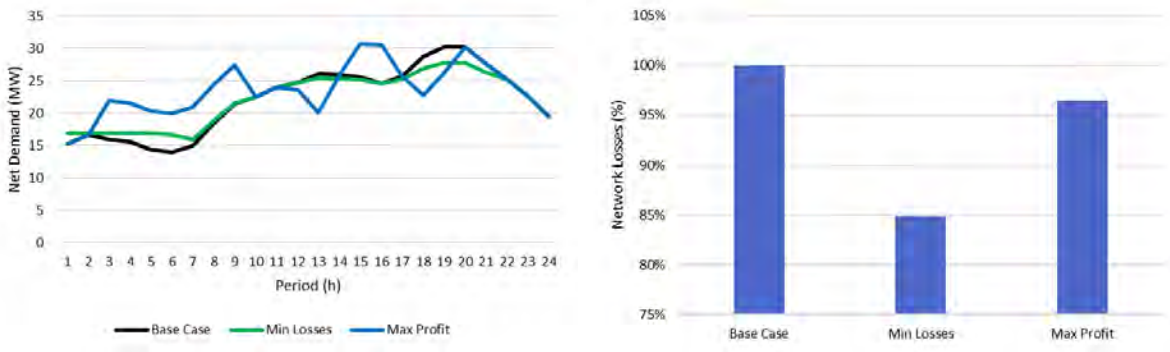



Figure 4.18. (a) Net demand and (b) network losses corresponding to the Base Case, Min Losses and Max Profit operating policies

Figure 4.19 illustrates the energy storage power and energy levels corresponding to these three operating policies. Application of the *Max Profit* policy results in additional charging / discharging cycles with respect to the *Min Losses* policy, since storage operation is driven by the energy market price differentials.

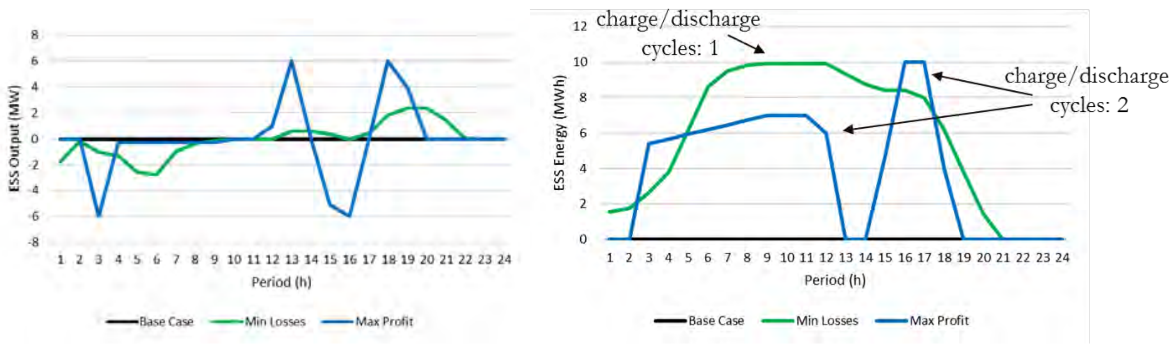



Figure 4.19. Storage (a) output and (b) energy level corresponding to the Base Case, Min Losses and Max Profit operating policies

Charging and discharging actions by energy storage are subject to energy losses given its round-trip efficiency. Therefore, a comprehensive analysis needs to account for these losses apart from network losses. Figure 4.20 presents both network and storage losses corresponding to different operating policies. Although energy storage reduces network losses (with respect to the *Base Case*) under all the examined operating policies, the total losses are higher than the *Base Case* due to the significant round-trip losses of storage (its round-trip efficiency is assumed 90% in this case), even if a *Min Losses* policy is adopted. Furthermore, it should be noted that *Max Profit* and *Optimized* operating policies do not only lead to higher network losses with respect to the *Min Losses* policy, but they also yield higher storage losses due to the additional charging / discharging cycles they entail (Figure 4.19).

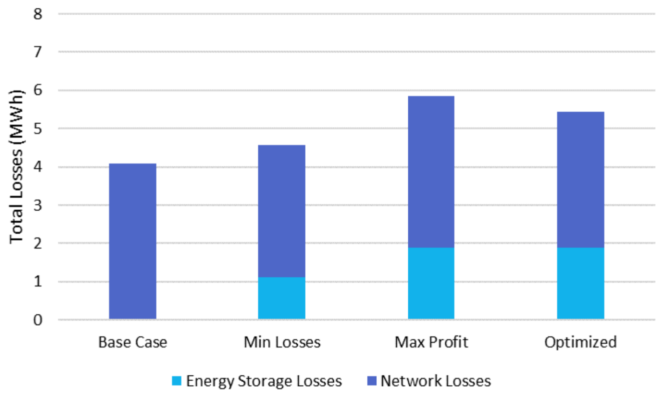



Figure 4.20. Network and storage losses corresponding to different operating policies

Beyond its round-trip efficiency, the performance of storage depends on other factors such as its power and energy capacity. Figure 4.21 presents the reduction in network losses achieved by the adoption of the Min Losses operating policy with respect to the Base Case, under different scenarios concerning the round-trip efficiency, the power capacity and the energy capacity of storage.

As the round-trip efficiency increases, the performance of storage in reducing network losses is enhanced, as storage can efficiently shift more demand from peak to off-peak periods without increasing excessively its own energy losses. The same effect emerges when the energy capacity of storage is increased, since storage has the capability to shift more demand from peak to off-peak periods. In contrast, an increase in active power capacity has no effect on the performance of storage.

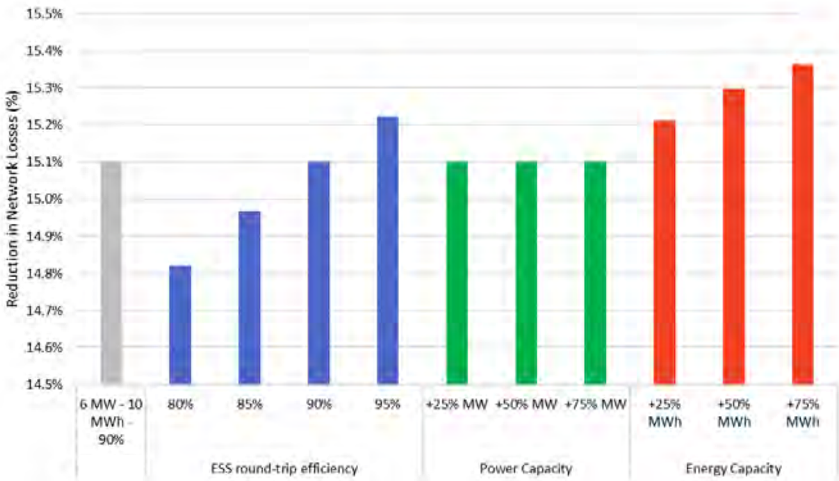



Figure 4.21. Reduction in network losses achieved by the adoption of the Min Losses operating policy with respect to the Base Case, under different scenarios concerning the round-trip efficiency, the power capacity and the energy capacity of storage

In addition to its capability to reduce network losses by means of active power charge / discharge actions, energy storage can further reduce network losses through reactive power actions, given the advanced reactive control capabilities of modern inverters. Although the level of reactive power demand is significantly lower than the active power demand, this capability has a major impact on network losses. Figure 4.22 presents the active and reactive net demand profiles corresponding to the *Base Case*, the *Optimized* operating policy without considering the reactive control capability and the *Optimized* policy when considering the reactive control capability.

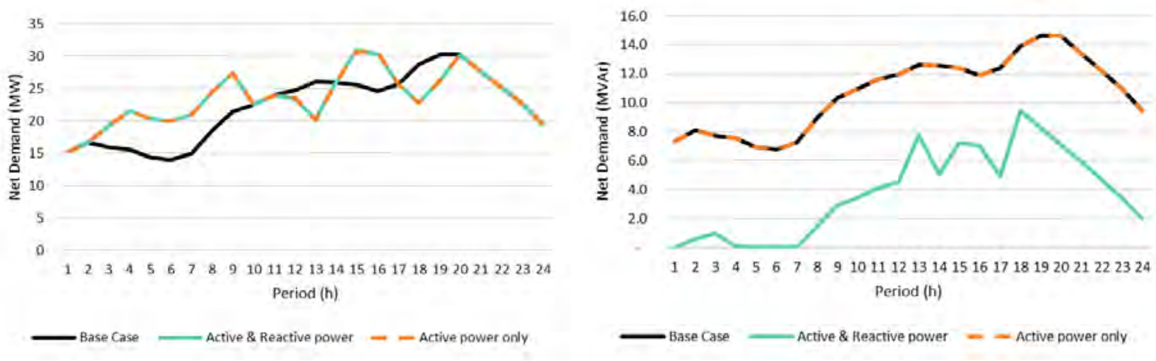



Figure 4.22. Net demand profiles of (a) active power and (b) reactive power corresponding to Base Case, Optimized operating policy without reactive power capability and Optimized operating policy when considering reactive power capability

Without reactive power control capabilities by the storage, the reactive power profile is given by the local demand and associated power factor. When storage exhibits such capabilities, it can modulate its reactive power output so as to reduce the reactive power flows and thus reduce overall network losses. It should be noted that in contrast to active power (charge/discharge) outputs which are limited by power and energy capacities (i.e. storage is required to recover its discharged energy) reactive power output is only limited by the storage rating. As a result, the overall network losses are significantly reduced when reactive control capability is available (Figure 4.23).

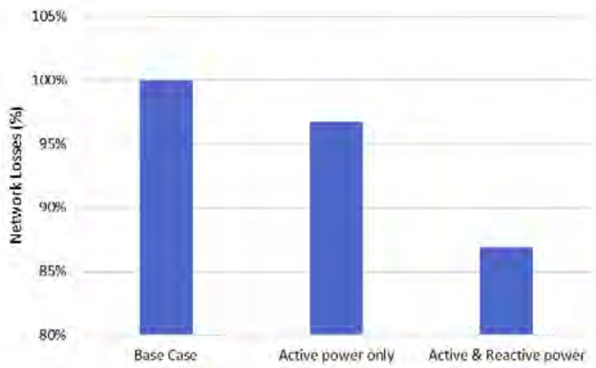



Figure 4.23. Network losses corresponding to Base Case, Optimized operating policy without reactive power capability and Optimized operating policy when considering reactive power capability

## 4.4 Summary

- Modelling demonstrated that the use of Quadrature Booster, beyond network constraint management as tested in the Flexible Plug and Play project, could deliver savings in local network losses from about 11% (in the case of high demand and high distributed generation (DG) growth) up to 25% for low demand and low DG growth.
- Smarter Network Storage installed in Leighton Buzzard could potentially reduce losses in supplying circuits by about 15%.
- Modelling demonstrated that the Soft open point (SOPs), installed for the management of constraints in LV feeders, could potentially reduce losses in the corresponding LV network and distribution transformers by about 10%-15%.

- Installing smart switchgear in HV networks could potentially reduce losses further by up to 10%, in addition to optimised NOP positions as described in Section 3.1.
- As indicated by Ofgem, the rollout of smart meters would lead to a reduction of energy demand of 2.8%. Modelling carried out demonstrated that this would potentially reduce distribution network losses for about 5.5%.
- Comprehensive analysis is carried out regarding the impact of demand redistribution on network losses, showing that demand side response, which could potentially shift 2.5% load from peak to off-peak period, would lead to reduction of losses by about 3%.

# 5 Identification of efficient loss reduction investment strategies

## 5.1 Eco-design: low-loss transformers

The contribution of transformer losses to the overall system losses is relatively significant (between 15% and 20%). Recent development in transformer technologies has yielded considerable reduction of transformer losses, which is important given the 30-40 years lifetime of the assets. Figure 5.1 shows load and no-load losses performance of 500 kVA (left) and 1000 kVA(right) transformers between pre-1955 and 2021 (future transformers).


Figure 5.1. Breakdown of transformer losses for different designs for 500 kVA (left) and 1000 kVA (right)

Both load and no-load power losses can be reduced substantially. For example, the pre-1955 transformer no-load losses are about 2.2 kW. This is expected to reduce to 0.2 kW by using the Eco-design low-loss transformers. Similarly, the load losses can be reduced by 33% from 12 kW to 8 kW. The use of copper instead of aluminium contributes to the significant reduction in losses with the associated drawback of heavier transformers.

In order to estimate the potential losses reduction if the use of Eco-design 2015 low-loss transformers is rolled-out widely across the UK Power Networks system, we use the 2016 data on the losses reduction attributed to the use of low-loss transformers for replacing the old distribution transformers in UK Power Networks (Table 13).

Table 13. Replacement of distribution transformers in 2016 (number)

| Area | Mounting | Asset Replacement | General Reinforcement | Total reduction of annual losses (MWh/year) |
|---|---|---|---|---|
| EPN | PMT | 0 | 12 | **12** |
| | GMT | 122 | 16 | **138** |
| LPN | PMT | 0 | 0 | **0** |
| | GMT | 59 | 3 | **62** |
| SPN | PMT | 0 | 3 | **3** |
| | GMT | 67 | 10 | **77** |
| **Total** | | **248** | **44** | **292** |

By analysing the UK Power Networks data, we have identified the possible number of transformer replacement for PMT and GMT in EPN, LPN, and SPN areas. Based on these figures, we estimate the total benefit of losses reduction. The results are presented in Table 14.

Table 14. Potential losses reduction by rolling out widely the use of Eco design low-loss transformers in UKPN

| Area | Mounting | Asset Replacement | General Reinforcement | Total |
|---|---|---|---|---|
| EPN | PMT | 0 | 51 | **51** |
| | GMT | 1,390 | 182 | **1,572** |
| LPN | PMT | 0 | 0 | **0** |
| | GMT | 743 | 38 | **781** |
| SPN | PMT | 0 | 10 | **10** |
| | GMT | 705 | 105 | **811** |
| Total | | **2,838** | **387** | **3,225** |

The total losses reduction is significant, i.e. 3,225 MWh per year. The capitalised value of this losses reduction is between £1.6-2.6m.

## 5.2 Amorphous Steel Transformers

Another different type of energy efficient transformer is an amorphous metal transformer (AMT). The magnetic core of this transformer is made with a ferromagnetic amorphous metal; the materials have high magnetic susceptibility, very low coercivity and high electrical resistance which lead to low eddy current losses. The no-load losses of AMT can be 70 – 80% lower than with traditional crystalline materials. This is demonstrated in Table 15 below where the no-load (NLL) and load losses (LL) performance of AMT for different types are compared against cold rolled grain oriented steel (CRGO) transformers. As shown in the table, while the load losses performance of both types of transformers is the same, the NLL of AMT are 63-79% lower than NLL of CRGO transformers.

Table 15. Comparison between losses performance of CRGO and Amorphous transformers

| Rating, kVA | Phases count | Voltage, kV | CRGO transformer | | Amorphous Transformer | | |
|---|---|---|---|---|---|---|---|
| | | | NLL | LL | NLL | LL | NLL reduction |
| **25** | 1 | 11/0.25 | 70 | 900 | 15 | 900 | -79% |
| **50** | 1 | 11/0.25 | 90 | 1100 | 22 | 1100 | -76% |
| **50** | 1 | 11/0.25-0-0.25 | 90 | 1100 | 22 | 1100 | -76% |
| **100** | 1 | 11/0.25-0-0.25 | 145 | 1750 | 38 | 1750 | -74% |
| **100** | 3 | 11/0.43 | 145 | 1750 | 53 | 1750 | -63% |
| **200** | 3 | 11/0.43 | 300 | 2750 | 90 | 2750 | -70% |

Based on the data above, we revise the figures in Table 14 by assuming the replacement of PMT using the AMT technology while other transformers are replaced with Eco-design low-loss transformers. The results are presented in Table 16. The losses reduction is slightly improved, from 3,226 MWh/year to 3,251 MWh/year due to the savings from AMT (26 MWh/year). This study did not take new PMT installations into consideration. The additional capitalised value of losses reduction is between £13-21k.

Table 16. Potential losses reduction by rolling out widely the use of Eco design and AMT low-loss transformers in UKPN

| Area | Mounting | Asset Replacement | General Reinforcement | Total |
|---|---|---|---|---|
| EPN | PMT | 0 | 72 | **72** |
| | GMT | 1,390 | 182 | **1,572** |
| LPN | PMT | 0 | 0 | **0** |
| | GMT | 743 | 38 | **781** |
| SPN | PMT | 0 | 15 | **15** |
| | GMT | 705 | 105 | **811** |
| Total | | **2,838** | **413** | **3,251** |

The study concludes that the deployment of low-loss transformers is essential to reduce losses; the benefit from the improvement of transformer technologies which is leading to the more efficient operation and reduction in losses should be capitalised. While the cost of low-losses transformers is relatively higher than the cost of traditional transformers, with mass deployment, the cost could be reduced. This will then make the proposition to use low-loss transformers more attractive.

## 5.3 Conductor Sizes Rationalisation

Another study investigated and quantified the level of loss reduction driven by increase in the minimum size of conductors. This strategy could be considered as a simplified variant of loss-inclusive design which optimises the size of conductors taking into account the long-term cost of losses altogether with the cost of conductors. In this study, load-flow analysis in carried out on the representative LV networks with different minimum conductor size policies: (i) base case (without minimum), (ii) 95 mm$^2$ as the minimum size for main conductors, then (iii) 185 mm$^2$ and (iv) 300 mm$^2$. The losses in each case are shown in Figure 5.2.

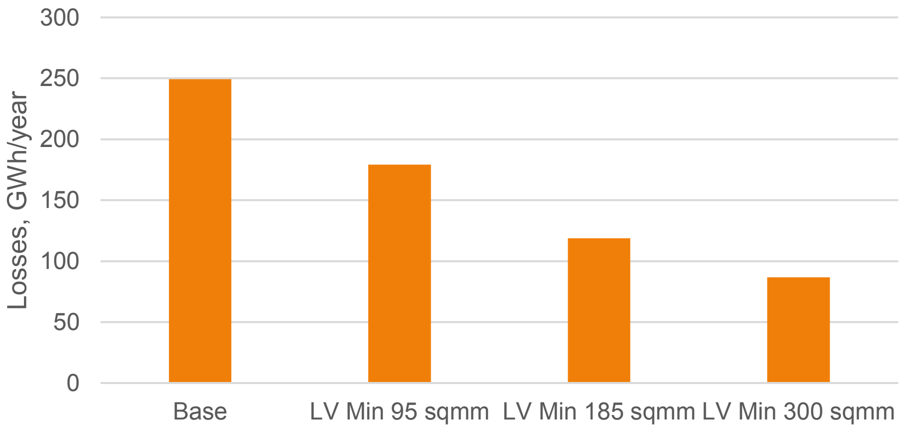



Figure 5.2. Losses on the representative LPN LV networks with different minimum conductor size policies

Increasing the minimum size of conductors will reduce losses; for example, if the minimum size is 95 mm$^2$, losses will decrease by 30%. Implementing higher minimum conductor size, e.g. 185 mm$^2$ and 300 mm$^2$ will yield higher losses reduction, i.e. 52% and 68% respectively (compared to the losses in the base case).

We simulated this policy on the LPN LV networks by creating the relevant representative networks for selected LV distribution sites (as shown on x-axis of Figure 5.3). The losses for different cases are presented in Figure 5.3.

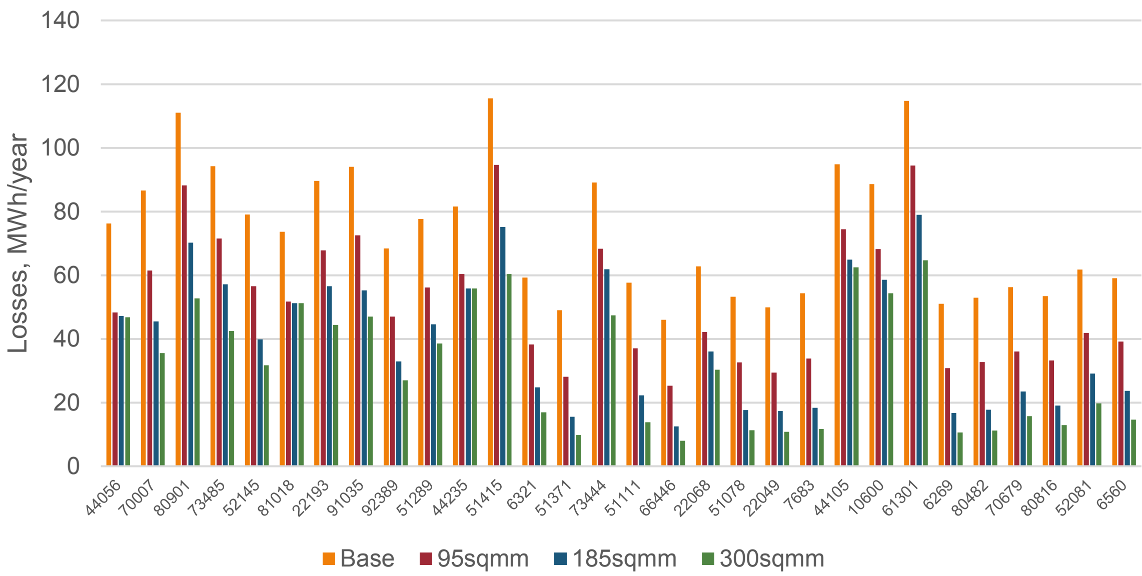



Figure 5.3. Impact of increasing the minimum size of conductors on the LPN LV networks

Depending on the number of feeders affected by this strategy, the level of losses reduction varies. If more feeders are affected, the losses reduction is higher. For the affected feeders, the reduction in losses due to increasing the conductor size also varies depending on the loading of the feeder in question.

In a similar fashion, we investigate and analyse the implementation of this strategy on the LPN HV network by carrying out simulations for the different minimum size of conductors: (i) 95 mm$^2$, 185 mm$^2$, and 300 mm$^2$. The total network length considered in this study is 10,335 km. The length of circuits affected by this policy is given in Table 17.

Table 17. The length of circuits affected by the minimum conductor size policy

| | **Min95** | **Min185** | **Min300** |
|---|---|---|---|
| **Replaced length, km** | 190 | 4,308 | 8,574 |

Increasing the minimum size of conductors affects more circuits, e.g. for 95 mm$^2$, the length of circuits that needs to be upgraded to meet the policy is 190 km. If 300 mm$^2$ is used as the minimum limit, then the length of the affected circuits is 8,574 km.

The results of the study on the LPN HV network are presented in Figure 5.4.The x-axis shows the distribution sites selected for this study. The annual losses are given on the y-axis.

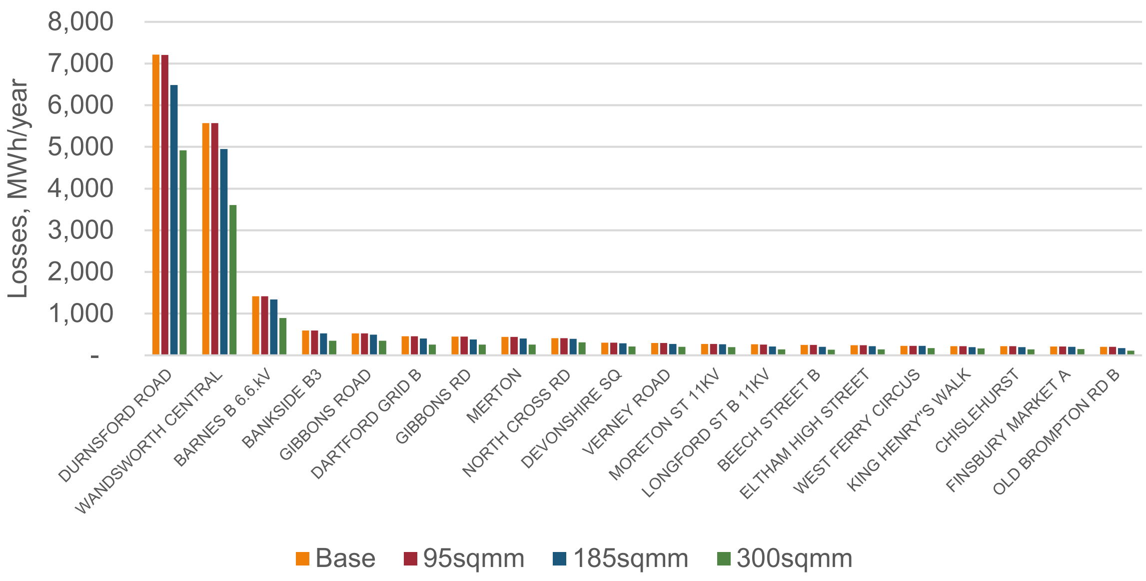



Figure 5.4. The impact of implementing minimum conductor size on LPN HV network losses

In LPN, the impact of the implementation of this policy varies across distribution sites. For example, for the network associated with Durnsfold Road, there is no HV feeder below 95 mm$^2$, so constraining the minimum size of the conductor to 95 mm$^2$ does not have any effect. However, when the minimum size is higher (e.g. 185 and 300 mm$^2$), the losses are lower by 8.5% and 31% respectively. The study also provides insight into the area of LPN where this policy would have the largest impact. For example: implementing this policy in the Durnsford Road area has larger impact than implementing this policy in the Wandsworth Central area. The distribution sites (on the x-axis) are ranked based on the level of losses (from high to low) in the base case. This will provide insight on which areas this policy should be implemented first.

The capitalised value of potential losses reduction in LPN LV and HV networks if the minimum conductor size is 185 mm$^2$ are between £63-104m and £1.1-1.8m, respectively.

In a similar fashion, the study was carried out in the LV and HV networks in the EPN and SPN areas. The reduction in losses in EPN LV network is shown in Figure 5.5. The findings are similar to those in LPN. For example, if the minimum size is 95 mm$^2$, losses will decrease by 35%. Implementing a higher minimum conductor size, e.g. 185 mm$^2$ and 300 mm$^2$ will yield higher losses reduction, i.e. 60% and 75% respectively (compared to the losses in the base case). The level of losses reduction in EPN LV networks is slightly higher than in the LPN networks, as the latter has a smaller number of circuits affected by the policy.

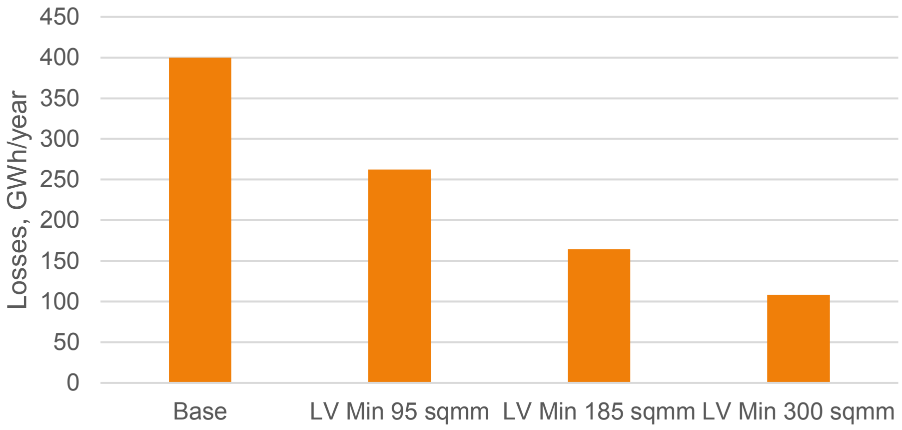



Figure 5.5. Losses on the representative EPN LV networks with different minimum conductor size policies

Figure 5.6 shows the losses reduction for implementing the policy on the EPN LV networks. The results indicate that many feeders in the EPN area will be affected by this policy, and this can substantially reduce the losses in EPN.

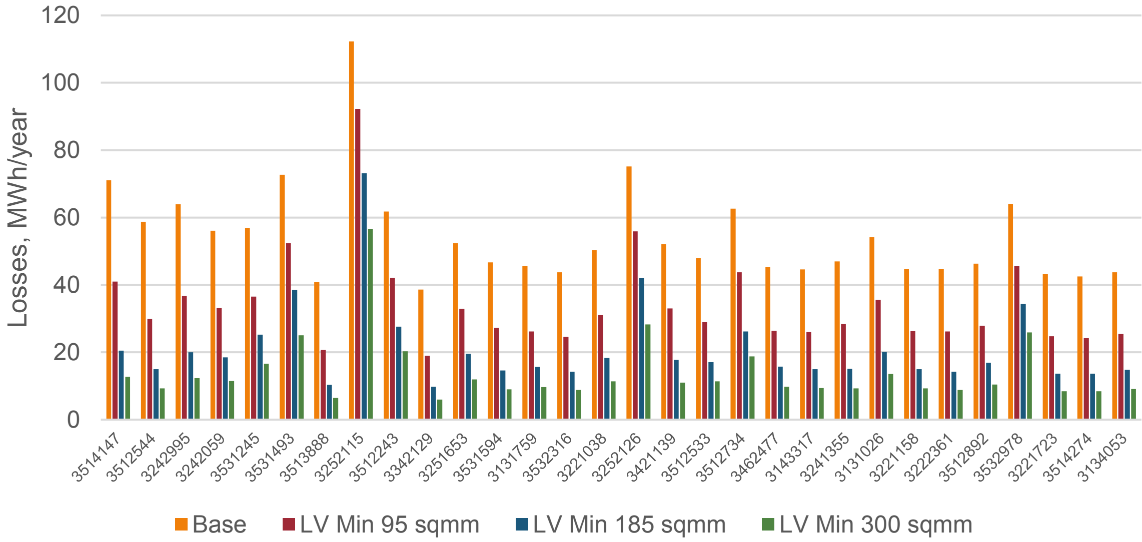



Figure 5.6. Impact of increasing the minimum size of conductors on the EPN LV networks

In a similar fashion, we investigate and analyse the implementation of this strategy on the EPN HV network by carrying out simulations for the different minimum size of conductors: (i) 95 mm$^2$ and 185 mm$^2$. The total network length considered in this study is 33,559 km. The length of circuits affected by this policy is given in Table 18.

Table 18. The length of circuits affected by the minimum conductor size policy in EPN

| | **Min95** | **Min185** |
|---|---|---|
| **Replaced length, km** | 18,344 | 26,968 |

The results of the study on the EPN HV network is presented in Figure 5.7.

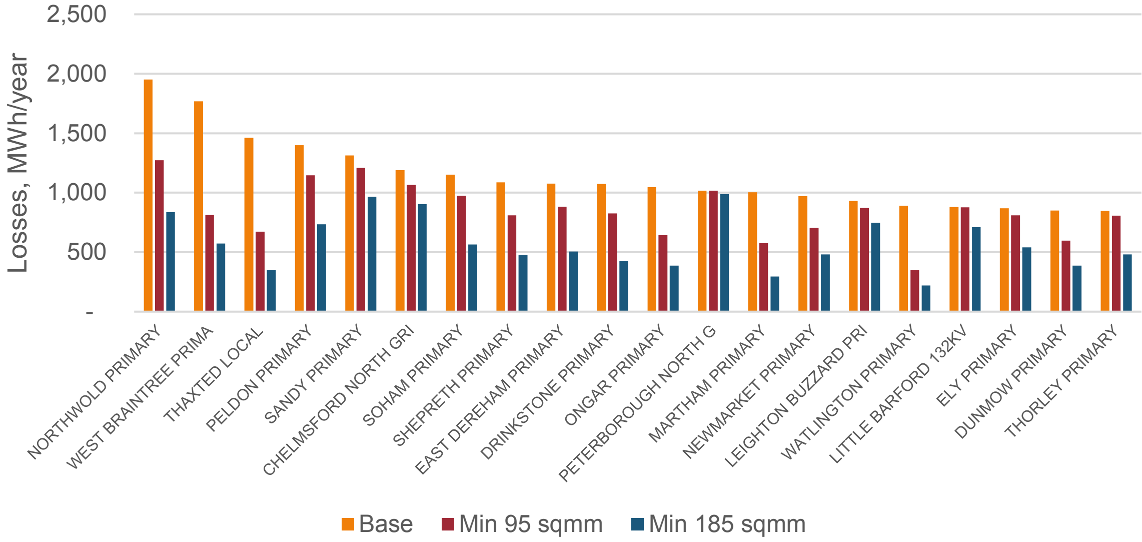



Figure 5.7. The impact of implementing minimum conductor size on EPN HV network losses

Similar to the findings for LPN, the impact of the implementation of this policy in EPN varies across distribution sites. The primary substation IDs (on the x-axis) are sorted based on the level of losses (from high to low) in the base case. In this case, the primary substation at Northwold primary is the first potential candidate for implementing this strategy.

The capitalised value of potential losses reduction in EPN LV and HV networks if minimum conductor size is 185 mm$^2$ are between £114-188m and £24-39m, respectively.

We also performed the study for the LV and HV networks in the SPN area. The losses reduction in SPN LV network is shown in Figure 5.8. The findings are the similar to LPN and EPN. For example, if the minimum size is 95 mm$^2$, losses will decrease by 20%. Implementing higher minimum conductor size, e.g. 185 mm$^2$ and 300 mm$^2$ will yield higher losses reduction, i.e. 47% and 64% respectively (compared to the losses in the base case). The level of losses reduction in SPN LV networks is comparable to LPN networks and slightly lower than EPN networks.

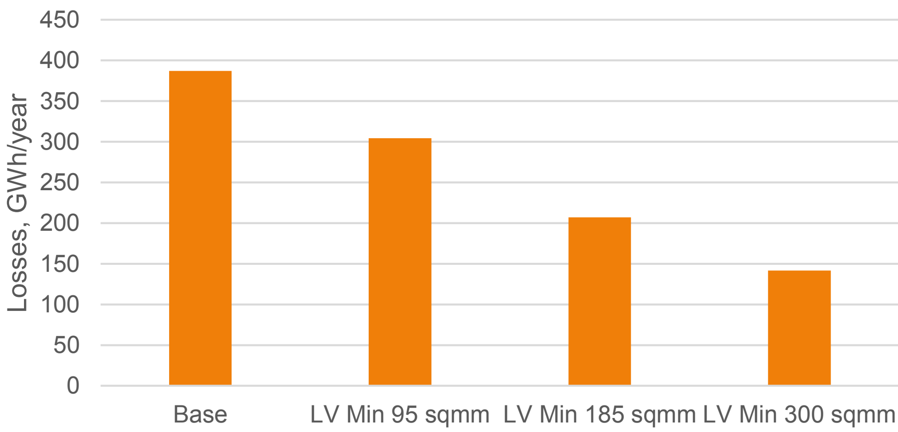



Figure 5.8. Losses on the representative SPN LV networks with different minimum conductor size policies

Figure 5.9 shows the losses reduction for implementing the policy on the SPN LV networks. The results indicate that many feeders in SPN area will be affected by this policy and this can substantially reduce the losses in SPN.

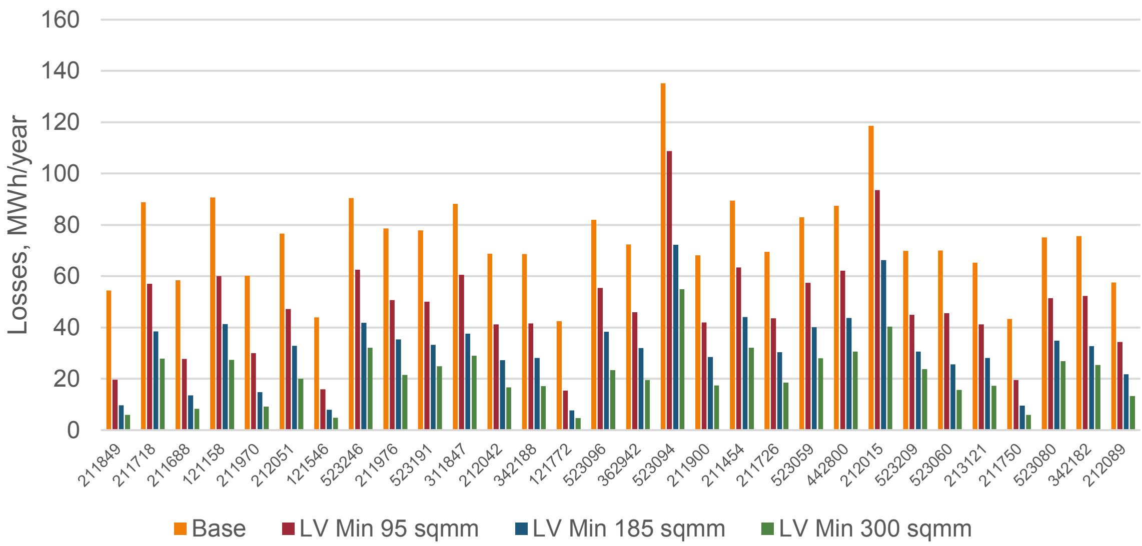



Figure 5.9. Impact of increasing the minimum size of conductors on the EPN LV networks

In a similar fashion, we investigate and analyse the implementation of this strategy on the SPN HV network by carrying out simulations for different minimum conductor sizes: (i) 95 mm$^2$ and 185 mm$^2$. The total network length considered in this study is 17,701 km. The potential for losses reduction on the HV network if minimum cable/conductor is Al 95 mm$^2$ or 185 mm$^2$ is about 15% or 32% respectively as shown in Figure 5.10. The length of HV circuits in SPN affected by this policy is given in Table 19.

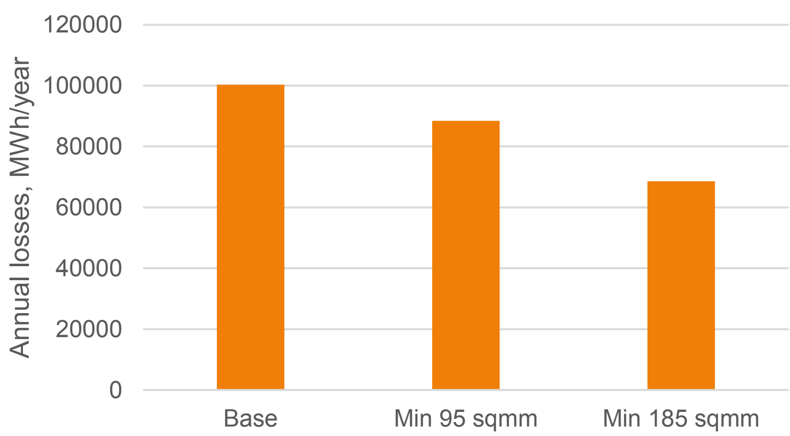



Figure 5.10. Losses on the representative SPN HV networks with different minimum conductor size policies

Table 19. The length of circuits affected by the minimum conductor size policy in SPN

| | Min95 | Min185 |
|---|---|---|
| **Replaced length, km** | 8,244 | 13,961 |

Similar to the findings for LPN and EPN, the impact of the implementation of this policy in SPN also varies across distribution sites, as presented in Figure 5.11. The primary substation IDs (on the x-axis) are sorted based on the level of losses (from high to low) in the base case. In this case, the primary substation at Shepway primary has the largest losses and becomes the first potential candidate for implementing this strategy in SPN.

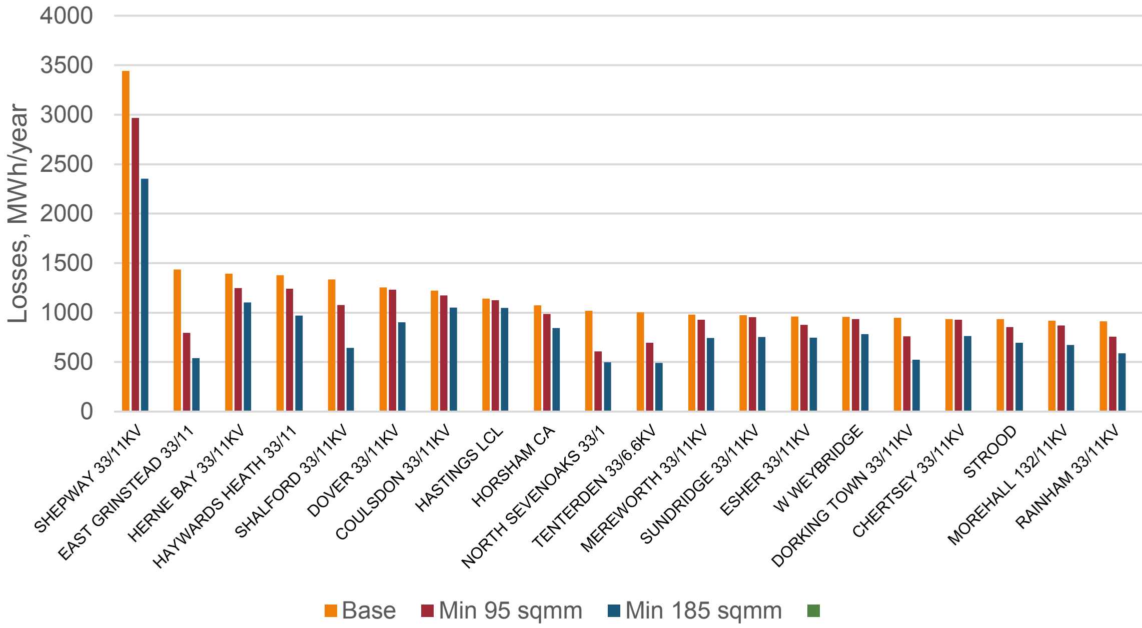



Figure 5.11. The impact of implementing minimum conductor size on SPN HV network losses

The capitalised value of potential losses reduction in EPN LV and HV networks if minimum conductor size is 185 mm$^2$ are between £87-144m and £15-25m, respectively.

## 5.4 Voltage rationalisation

### 5.4.1 HV networks

UK Power Networks inherits the legacy of operating 2.2, 3.3, and 6.6 kV systems in some of its areas; these systems were designed decades ago and may no longer fit for future. As the systems are aging and may reach its lifetime, there is an opportunity to upgrade these systems to 11 kV or 20 kV to reduce losses. In order to analyse the level of losses reduction that can be achieved, we carried out a set of studies quantifying the reduction in losses attributed to the replacement of those systems with 11 or 20 kV systems. We assume that the network topology will not change and the replacement is done on a like-for-like basis. The study was performed on the SPN networks. The results are presented in Table 20.

Table 20. The benefit (losses reduction) of moving to a higher voltage level

| Voltage | Length, km | Potential for losses reduction at 11 kV, MWh/year | Potential for losses reduction at 20 kV, MWh/year |
|---|---|---|---|
| 2.2 | 99 | 183 | 188 |
| 3.3 | 74 | 1,597 | 1,707 |
| 6.6 | 2,180 | 13,402 | 18,660 |
| 11 | 15,347 | 0 | 100,260 |
| Total | 17,701 | 15,181 | 120,815 |

Table 20 shows the length of circuits operate at 2.2, 3.3, 6.6, and 11 kV in SPN. The table also shows the reduction in losses if all the corresponding circuits are operated at 11 kV or 20 kV. If the voltage level can be standardised to 11 kV, the losses could be reduced by about 15 GWh/year (worth about £0.73-1.2 million per year). This will involve upgrading about 2,300 km of network. If, rather than 11 kV, the HV voltage level is standardised to 20 kV, then the losses could decrease by around 121 GWh/year (worth of £59-97 million). This would involve an upgrade of about 17,700 km of network. In this study, the changes in transformer losses are not analysed.

### 5.4.2 EHV networks

Another study we carried out investigated the losses impact of replacing the 33 kV system with a 132 kV system. In this study, we simulate the situation where all 33 kV network in the LPN region (about 6,100 km circuits) is upgraded to 132 kV. The study indicates that the expected reduction of losses reaches 24 GWh/year, which is worth between £12-19 million (capitalised value). In this study, the potential changes in transformer losses are excluded from the analysis.

## 5.5 Smart distribution transformer

As previously discussed in section 6.2-6.5, improvement of power factor, optimisation of operating voltage, and balancing the load across AC phases could be an effective strategy to reduce losses. Smart distribution transformers can provide all the above functionality to improve the overall efficiency of distribution networks. In this context, we analyse the losses reduction potential of such technology. We assume that the smart distribution transformers can reduce the imbalance by 10%, improve the power factor, and also support voltage optimisation. This results in more than 13% losses reduction: 5% reduction from reducing the load imbalance and to the remainder from improved power factor and voltage optimisation. The study was carried out on selected LV systems in the EPN region. The level of losses (left y-axis of Figure 5.12) and the associated reduction (y-axis on the right) attributed to different functionalities are shown in the figure below for each selected distribution site (shown on the x-axis).

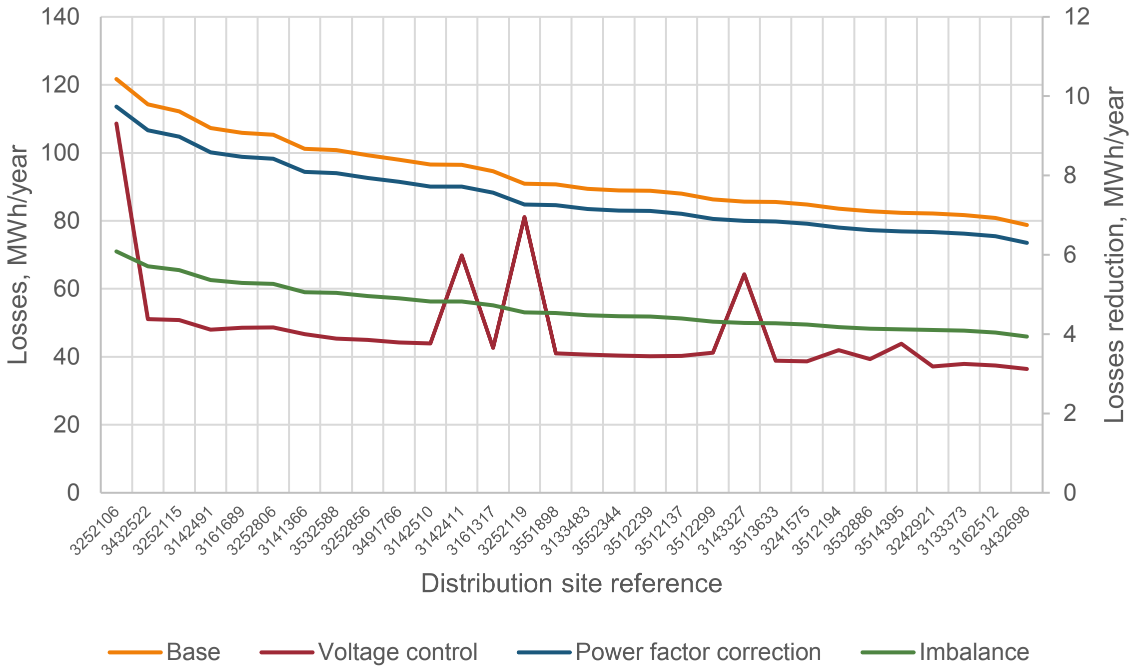



Figure 5.12. Benefit of deploying smart distribution transformers in EPN region.

In total, the reduction in losses due to the use of smart distribution transformers is around 58,328 MWh/year, which correspond to the range of capitalised savings between £28-47m.

## 5.6 Scott Connected Transformers

A Scott-T (also called a Scott connected) transformer is a type of circuit used to obtain two-phase power from a three-phase source or vice versa. The Scott-T transformer is built with two single-phase transformers of equal power rating. The MAIN and Teaser sections can be enclosed in a floor mount enclosure with MAIN on the bottom and Teaser on top with a connecting jumper cable. They can also be placed side by side in separate enclosures. Due to this configuration, the losses in this two-system two-phase networks are about twice the losses in a conventional three phase system, conservatively assuming losses are 50% greater due to imbalance.

Because of this legacy system, there are still a number of Scott-T transformers operated by UK Power Networks. Upgrading these transformers to three-phase transformers is a potential strategy to reduce losses. In this context, we analyse and estimate the level of savings in losses due to the upgrade of this type of transformers. The 30 most prominent distribution sites and the level of losses reduction that can be expected if the Scott-T transformers are replaced by the equivalent 3-phase transformers are listed in Table 21.

In the table, the 30 most prominent distribution sites are listed according to potential losses reduction (highest on top). The potential losses reduction varies between 40-79 MWh/year per site. However, there are about 307 Scott-T transformers in the SPN licence area. The total potential losses reduction if all Scott-T transformers are replaced by three-phase transformers is 6,635 MWh/year. The corresponding capitalised value is between £3.2-5.3m.

Table 21. List of distribution sites with Scott-T transformers and the potential losses reduction if they are replaced by 3-phase transformers.

| Site Reference | List name | Losses annual savings (MWh/year) |
|---|---|---|
| 212139 | ENMORE ROAD | 78.6 |
| 212197 | ASHBURTON ESTATE | 73.3 |
| 212015 | ELY ROAD SB | 66.5 |
| 211522 | ST AUGUSTINES AVE SB | 59.5 |
| 212160 | MORELAND AVENUE | 58.9 |
| 211990 | PENRITH ROAD | 55.0 |
| 211840 | WHITEHALL ROAD | 54.6 |
| 211568 | EDGEHILL ROAD | 51.2 |
| 211825 | ST JAMES ROAD | 50.3 |
| 212145 | CRAVEN ROAD | 50.1 |
| 212007 | SELHURST WELL | 48.4 |
| 212095 | DALMALLY PASS. SB | 48.2 |
| 212141 | LONGHEATH SB | 47.7 |
| 212068 | SYLVAN HILL | 47.1 |
| 211950 | ST.JOSEPHS COLLEGE | 47.0 |
| 212001 | RYEFIELD ROAD | 46.0 |
| 212165 | LESLIE PARK ROAD | 45.8 |
| 212004 | ALL SAINTS | 45.5 |
| 211922 | CRAIGNISH AVENUE | 45.1 |
| 212167 | BINGHAM ROAD SB | 44.9 |
| 211892 | PRIORY ROAD | 44.6 |
| 212072 | STONEY LANE SB | 44.4 |
| 211912 | BRIAR ROAD SB | 42.2 |
| 211948 | VIRGINIA ROAD | 42.1 |
| 211902 | FOREST GARDENS | 41.6 |
| 212143 | SPRING LANE SB | 41.0 |
| 211718 | CROHAM ROAD SB | 40.7 |
| 211669 | EPSOM ROAD SB | 40.6 |
| 211930 | HILLCOTE AVE SB | 40.1 |
| 211690 | LOWER COOMBE STREET | 39.8 |

## 5.7 Impact of Distribution Transformer Density

The density of distribution transformers is another important factor with respect to the level of losses in the network. Results on analysis aiming at capturing this dependency are presented in Figure 5.13, assuming a typical 1979 distribution transformer losses specification. When the density of distribution transformers is lower (7 DTs/km$^2$), LV feeders supplying the load need to be longer and more loaded, which results in greater losses on LV networks (indicated by LL) and load losses of distribution transformers (indicated by DT LL). As a result, losses in the HV network (indicated by HV) are also higher, given that this network supplies the LV network. However, when density of distribution transformers is higher (14 DTs/km$^2$), the distribution transformer no-load losses (indicated by DT NLL) are greater.

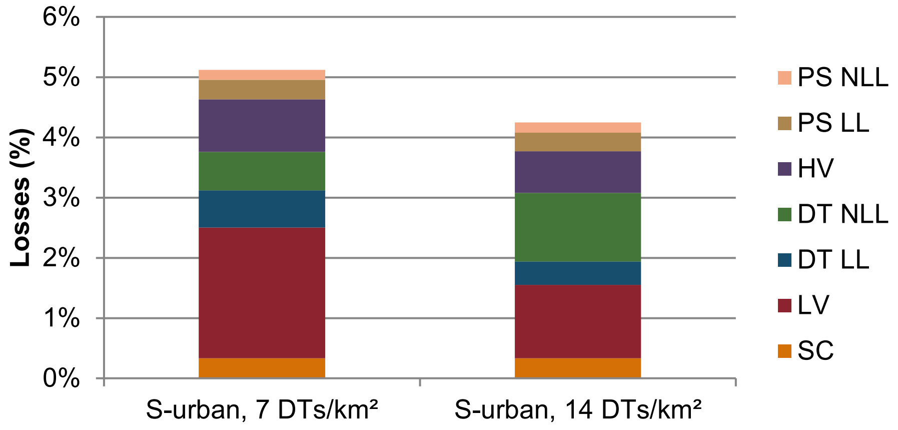



Figure 5.13. Breakdown of total losses in semi-urban networks for different densities of distribution transformers.

Losses in service cables (indicated by SC) and LV networks account for almost 50% of the total losses in networks with a lower density of distribution transformers while this percentage drops to 37% for a higher density. Distribution transformers' load losses also drop from 12 to 9% while distribution transformers no-load losses increase from 13% to 27%, as illustrated in Figure 5.14.

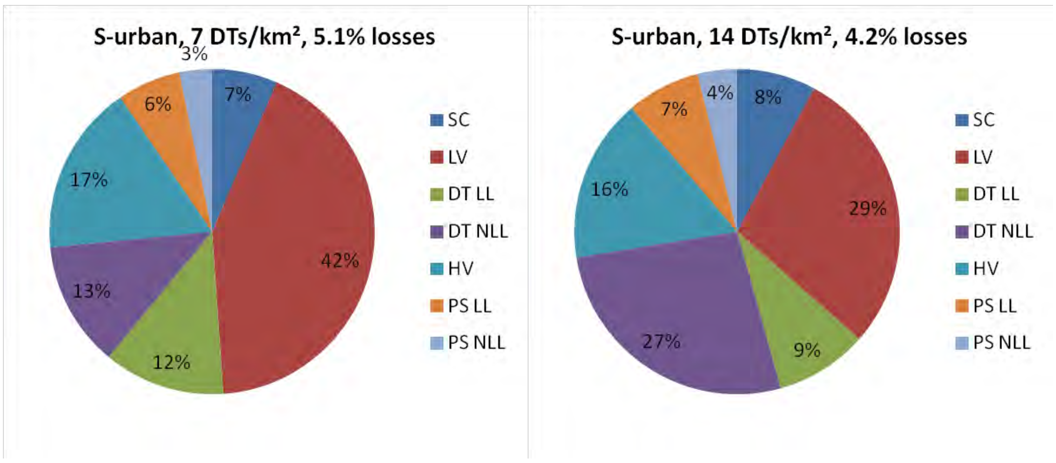



Figure 5.14. % breakdown of total losses in semi-urban networks for different densities of distribution transformers.

Potential losses reduction by doubling the number of distribution transformes in semi-urban networks are on average about 26%.

Figure 5.15 and Figure 5.16 present the respective breakdown of total losses for semi-rural networks. The trends are similar, with the most important difference being the higher proportion of HV network losses.

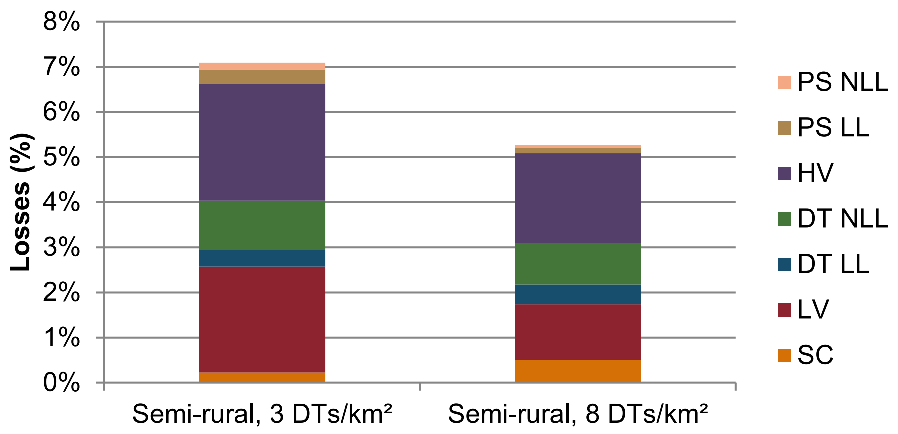



Figure 5.15 Breakdown of total losses in semi-rural networks for different densities of distribution transformers.

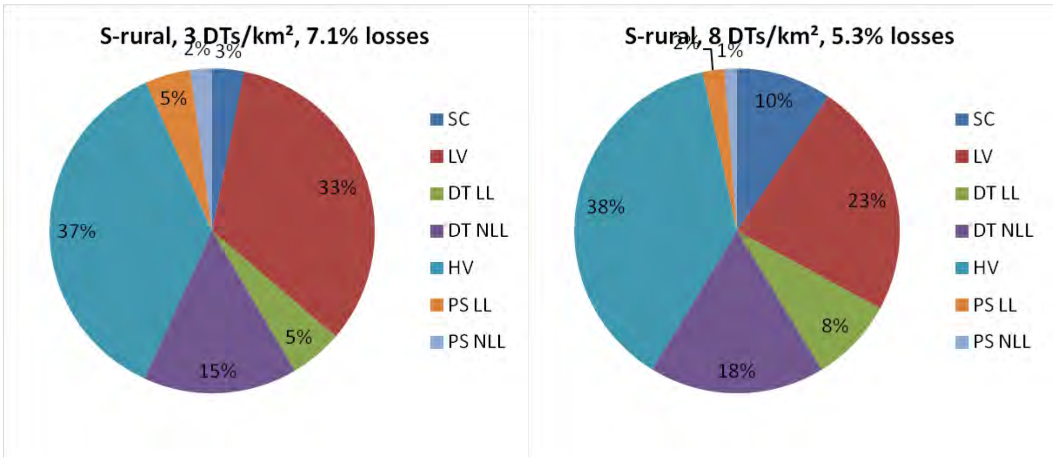



Figure 5.16 % breakdown of total losses in semi-rural networks for different densities of distribution transformers.

Potential losses reduction by increasing the number of distribution transformers in semi-urban networks are on average about 17%.

## 5.8 Impact of tapering

The effect of tapering was investigated using a model of tapered cable as shown in Figure 5.17.

Figure 5.17: Tapered cable model.

The specified section model had the following characteristics:

- The first section of 120 meters is 300 mm$^2$ cable
- The second section of 114 meters is 185 mm$^2$ cable
- The final section of 166 meters is 95 mm$^2$ cable
- There are 130 connected customers uniformly distributed along the cable

- Diversified peak demand of 1.2 kW and coincidence factor[13] of 0.1 are used to estimate load and flow along cable
- Power factor of 0.96
- Peak utilisation of 100%

A coincidence factor is used to calculate the length of each tapered section such that none of sections is overloaded at peak condition.

In this configuration, tapered cables increase losses by up to 25%. If cable peak utilisation were lower the losses increase would be lower.

## 5.9 Summary

- A detailed analysis of non-load related replacement of distribution transformers is carried out. If all distribution transformers classed by Health Index 4 and 5 are replaced by the Eco design transformers the potential for losses reduction is 17 GWh per annum in the UKPN area. Given the rate of annual replacement of distribution transformers, the savings in losses could be potentially about 3.2 GWh per year.
- Once conditionally driven cable reinforcement is needed, investment in high-capacity cables would be economically efficient for reduction in losses. However, it should be noted that cables replacement is not driven by losses. Analysis was carried out to determine the benefits in loss reduction by adopting minimum feeder cross section area of 185 $mm^2$. This would lead to reduction in losses in HV network in LPN area of 10% and EPN 40% and SPN 32%. For LV networks, the benefits could be up to 52-63% depending on the area.
- Given that service cables typically supply a single customer, quantification of losses based half-hourly energy consumption may underestimate losses. To inform this process, analysis of losses is carried out using 5,000 five-second daily profiles and compared with the amount losses obtained when half-hourly profiles are used. The actual losses are on average 1.9 times greater compared with the losses calculated using half-hourly profiles (the range is wide from 1.2 to 5.8), which will clearly impact the choice of cross-sectional area of service cables.
- If single-phase HV spurs are converted to three phase, losses could be potentially reduced by up to 80% in the corresponding network. Assuming the neutral path has the same resistance as the phase conductor, this conclusion is independent from circuit loading and conductor cross sectional area.
- Increasing the number of distribution transformers could potentially reduce losses between 17-26%.
- Removing tapering could potentially decrease losses by up to 25%.

[13] Coincidence and diversity factor are assumed to be directly opposite and proportional i.e. multiplying each other gives 1. The coincidence factor is lower than or equal to 1 and the diversity factor is greater than or equal to 1.

# 6 Conclusions

Comprehensive studies have been carried out to investigate losses drivers and to identify opportunities and strategies for reducing network losses through improving system operation, system design, and deploying loss-reduction technologies. The analysis quantified the effectiveness of alternative strategies and identified the priority areas in UK Power Networks.

In order to carry out this analysis, a new modelling tool, called Loss Operation & Investment Model (LOIM) was developed for detailed quantification of losses in real distribution networks, from low voltage networks to grid supply points. This is in contrast to previous analyses of network losses based on the application of representative distribution networks[14]. The LOIM has also been applied to generate Losses Heat Maps for UK Power Network areas in order to identify regions in which the volume of network losses are most significant. The effectiveness of various network loss-reduction techniques in different UKPN areas was analysed in detail. Core insights were produced regarding the business case for alternative loss mitigation strategies and loss-driven network infrastructure investment.

The key findings of this work can be summarised as follows:

**Quantification of network losses**

The analysis carried out highlighted that more than 75% of network losses are associated with LV networks, HV networks and distribution transformers. Overall:

- 36-47% of the total losses are in LV networks
- 9-13% of losses are associated with distribution transformer load related losses
- 7-10% of losses are associated with distribution transformer no-load losses
- 17-27% are in HV networks
- 17-24% of total losses are in primary and grid transformers, and EHV and 132 kV networks.

Understanding the contribution of different network sections to the total losses will be important when identifying loss management strategies, assessing corresponding cost effectiveness and determining the potential impact of those strategies.

**Distribution of losses across network segments**

Asset utilisation and circuit lengths are major losses drivers and hence their impacts have been investigated and analysed across each region. UK Power Networks operate a wide range of network types. These range from rural areas, such as parts of Norfolk and Suffolk, to very densely populated urban areas like London. The corresponding peak demand density varies from a very low 0.05 MW/km$^2$, to a relatively high density of 137 MW/km$^2$. In this context, average utilisations of distribution transformers of 51% and 38% are observed in LPN and EPN areas respectively.

Furthermore, the proportion of transformers which have a utilisation factor in excess of 70% in LPN is 20%, while in EPN this figure is only 4%.

Detailed power flow modelling revealed that HV feeders in LPN deliver an average of 50% more energy than feeders in EPN, while circuits in LPN are typically about 60% shorter than in the EPN region. In this context, the analysis demonstrated that losses in LPN are primarily

[14] Imperial College London and Sohn Associates, *Management of electricity distribution network losses*, supported by UKPN and WPD, 2014

driven by high network utilisation, while in EPN, losses are driven by long feeder lengths. Overall, the LV network losses are comparable in both areas despite LPN LV networks having significantly shorter lengths but higher loading. Conversely, losses in the HV networks are greater in the EPN region.

The analysis demonstrated that the magnitudes of losses vary significantly across each network type. Modelling quantified losses for more than 4,000 HV feeders, demonstrating a relatively small number of HV feeders are characterised with high losses. About 70% of the total losses are in 20% of the feeders. This clearly demonstrates that loss reduction initiatives in HV networks should target a relatively small proportion of the feeders characterised by these high losses. Undertaking a targeted approach will maximise the cost efficiency of this activity. An unequal distribution of losses was noted in the LV network with more than 50% of losses noted to occur in only 20% of LV feeders.

Based on advanced neural networks methodology, UK Power Networks' HV feeders and LV networks were classified into 22 clusters. These clusters were determined according to the number of customers and their load characteristics, network length, rating, type and construction. Average parameters for each cluster were quantified and corresponding representative networks created. These included a range of rural and urban networks, and the related loss performance for each was assessed.

As a significant amount of losses are associated with a small number of very specific feeders, it should be noted that use of generic feeders with average parameters may not provide appropriate evidence to inform the development of effective losses reduction strategies.

**Identification of potential operational strategies for loss reduction**

A number of key losses drivers were identified and analysed. Learning from this analysis can be used to inform the development of future losses reduction strategies. These include changes in network operational topology, improvement of power factor, changes in load profile, controlling phase imbalance and harmonic distortion.

Key results of conducted case studies are as follows:

- Analysis demonstrated that Normally Open Point (NOP) reconfiguration could reduce HV feeder losses by up to 15% in specific areas. The economic case for this operational strategy, as a result, appears to be strong.
- For the three UK Power Networks licence areas feeders are ranked by the possible reduction in losses driven by power factor improvement. The potential for loss reduction is assessed assuming power factor improvement from 0.85 to 0.95. This would lead to reduction in losses on each feeder between 11% and 14%. It is interesting that the modelling demonstrated that improving power factor in only one third of HV feeders could achieve 90% of potential losses reduction. Hence, the list of 30 highest ranked HV feeders in each licence area is created and measurements of the actual power factor in future trials are proposed to be carried out.
- It was noted that phase imbalance increases losses non-linearly. For example, phase imbalance ranging from 10% to 30% would increase losses by 5% to 45% respectively. As a consequence, we identified a list of 30 LV networks that would deliver the highest benefits for imbalance improvement, based on the networks' electrical characteristics.
- Implementing voltage management across UK Power Networks' three licence areas could potentially reduce losses by around 5%. Further investigation is required to understand the voltage dependency of customer loads. Measurements are recommended to enhance the understanding of voltage dependency in real time. This information will aid the formation of future loss mitigation strategies. Performing actual measurements of voltage

dependency of demand in different segments of the network should provide key information related to the potential development of corresponding loss mitigation strategies.

- Harmonic distortion is limited though network design standards, which ensure that the impact of harmonic currents on networks are limted. The impact of voltage harmonics on transformer no-load losses is linearly dependant on the total harmonic distortion (THD), and hence, the impact on losses in this domain is more significant. Eco design transformers' iron losses are lower than previous transofmer specifications. The net effect of this should mean that the impact of harmonic distortion on no-load losses will decrease over time.

**Application of smart-grid technologies for reduction of network losses**

- Modelling demonstrated that the use of UK Power Networks' Quadrature Booster, beyond the network constraint management utilised by their Flexible Plug and Play (FPP) project[15], could deliver savings in the local network losses from about 11% in the case of high demand and high distributed generation (DG) growth, up to 25% for low demand and low DG growth.
- Furthermore, modelling demonstrated that optimally controlling the power factor of distributed generators in the FPP project area could potentially reduce 33kV network losses by 13%.
- Smarter Network Storage (SNS)[16] installed in Leighton Buzzard to manage peak demand and postpone network reinforcement (in addition to delivering system balancing services), could potentially reduce losses in supplying circuits by about 15%.
- Modelling demonstrated that Soft Open Points (SOPs)[17], installed for the management of constraints in LV feeders, could potentially reduce losses in the corresponding LV network and distribution transformers by about 10%-15%.
- Potentially further reduction in losses could be achieved by optimizing NOP positions in real time to take into account changes in demand and generation.
- The former Department of Energy and Climate Change (DECC) indicated that smart meters, combined with home display units, could reduce energy consumption by 2.8%[18]. Analysis showed that correspondingly, distribution network losses would reduce by 5.5% due to the decrease in consumption.
- Furthemore, analysis demonstrated that demand side response, which could potentially shift 2.5% load from peak to off-peak period, would lead to a reduction of losses by about 3%.

**Identification of efficient loss reduction investment strategies**

- UK Power Networks could save 17GWh per annum by replacing all Health Index 4 and 5 distribution transformers with Ecodesign units. Given the current rate of replacement, savings could reach up to 3.2 GWh per year.
- Loss reduction benefits alone are not sufficient to justify the upgrade of existing underground cables. Howerver, when thermal constaints drive network reinforcement , installing cables of higher capacity would significantly reduce losses. In this context,

[15] http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Plug-and-Play-(FPP)/
[16] http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Smarter-Network-Storage-(SNS)/
[17] http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Urban-Networks-Low-Voltage/
[18] https://publications.parliament.uk/pa/cm201617/cmselect/cmsctech/161/161.pdf

analysis carried out to determine the benefits in loss reduction by adopting a minimum feeder cross-section area of 185 mm². This would reduce LPN HV feeder losses by 10%. The corresponding values for EPN and SPN are 40% and 32% respectively. Removing tapering could potentially decrease losses by up to 25%. For LV networks, the benefits of applying larger cables would be very significant, ranging from 52% to 63%, depending on the area.

- Using 30-minute samples tends to understate network losses, particularly in service cables that supply one customer only. To inform this process, 5,000 five-second samples from the Low Carbon London (LCL)[19] project were used comparatively. This modelling demonstrated that applying higher sampling rates increases calculated losses by a factor of 1.9 compared with the losses estimated using half-hourly profiles (the range is from 1.2 to 5.8). This further reinforces the case for significantly increasing the standard capacity of service cables.
- If single-phase HV spurs are converted to three phase, losses could potentially be reduced by up to 80% in the corresponding network.

**Benefits of loss reduction strategies**

Based on the analysis carried out, the capitalised value of the benefits associated with alternative loss reduction strategies are summarised in Table 22. The annual capitalised benefit is calculated by applying a discount rate of 3.5%.

Table 22 - Capitalised value of the benefits associated with alternative loss reduction strategies

| Strategy | Capitalised value | Comment |
|---|---|---|
| **NOP optimisation** | £5.4-8.9m | LPN area |
| **HV smart switches** | £2.6-4.3m | LPN area |
| **Multiple power factor correction per HV feeder** | SPN £48-80k<br>EPN £56-92k<br>LPN £53-88k | Minimum for 30 'best' HV feeders per each licence area if power factor is reduced from 0.85 to 0.95; the power factor is not yet measured and hence potential value might be lower of higher |
| **Single point power factor compensation per HV feeder** | SPN £25-41k<br>EPN £30-49k<br>LPN £28-46k | Minimum for 30 'best' feeders per each licence area if single point compensation is installed. Potential value depends on actual power factor |
| **Voltage control** | LV £1.5-2.4k per site<br>HV £9.2-15.2k per feeder | Maximum expected value for voltage dependent loads (constant power and constant impedance); for mixes different types of loads, i.e. constant power, constant current and constant impedance based loads, the benefits of voltage control are marginal. |
| **LV load balancing** | £0.9-13.6k per site | LPN LV network |
| **LV harmonics** | £200-300 per site | |

[19] http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Low-Carbon-London-(LCL)/

| Strategy | Capitalised value | Comment |
|---|---|---|
| **Primary transformer de-energisation during low load conditions** | Negligible | For typical transformer load and no-load losses, the benefit is negligible; in the event of high no-load losses relative to load losses[20], the potential benefit could be £49-81k per substation |
| **Eco-design transformers** | £4-7.4k per transformer | Average savings per transformer (392 transformers considered) |
| **Amorphous transformers** | £0.9-1.4k per PMT | Average savings per PMT transformer (15 pole mounted transformers (PMTs) considered) |
| **Conductors rationalisation** | LPN LV £63-104m<br>LPN HV £1.1-1.8m<br>EPN LV £114-188m<br>EPN HV £24-39m<br>SPN LV £87-144m<br>SPN HV £15-25m | All conductors lower than Al 185 mm² are replaced with Al 185 mm² conductors.<br>LPN HV network already uses relatively higher conductor sizes and hence benefit is relatively lower than in EPN and SPN. |
| **SPN HV voltage rationalisation** | Min 11 kV £7.3-12m<br>Min 20 kV £59-97m | - SPN HV voltages 2.2, 3.3 and 6.6 kV are upgraded to 11 kV, 2,300 km of conductors<br>- All HV voltages are upgraded to 20 kV, 17,700 km of conductors<br>- Impact of transformers is not taken into account |
| **LPN EHV voltage rationalisation** | £12-19m | LPN 33 kV network is upgraded to 132 kV, 6,100 km of conductors; Impact of transformers is not taken into account |
| **Smart distribution transformer21** | £7.4-12.3k per secondary site | Minimum benefit per site [considering EPN 30 'best' sites for voltage control on LV network (4% loss reduction), HV network (5% loss reduction), power factor improvement (8% loss reduction) and phase imbalance reduction (5% loss reduction)] |
| **Scott connected transformers** | £10.4-17.3k per site | SPN LV networks supplied from 307 Scott connected transformers |
| **Impact on transmission system** | Average savings on National Grid's networks of up to | Savings are due to reduced active power on UK Power Networks regions. Control of reactive power |

[20] High no-load losses imply older transformers, which based on life expectancy, could reduce the indicative value of the capitalised benefits as these might be replaced, based on condition, before the full benefits are achieved.

[21] Typically distribution transformers are equpted by off-load tap changers to adjust for a seasonal variation in expected voltage range. Smart distribution transformers could control voltage during operatioin in order to, for example, reduce losses.

| Strategy | Capitalised value | Comment |
|---|---|---|
| | 5.5% could be achieved | could potentially generate additional savings. |

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# 8 Acronyms

| | | |
|---|---|---|
| AMT | - | Amorphous Metal Transformer |
| CRGO | - | Cold Rolled Grain Oriented Steel |
| CSA | - | Cross Sectional Area |
| DT | - | Distribution Transformer |
| EPN | - | Eastern Power Network |
| GMT | - | Ground Mounted Transformer |
| GSP | - | Grid Supply Point |
| LDR | - | Losses Discretionary Reward |
| LF | - | Peak Load Factor |
| LL | - | Load Losses |
| LLF | - | Load Loss Factor |
| LOIM | - | Loss Operation & Investment Model |
| LPN | - | London Power Network |
| OPF | - | Optimal Power Flow |
| NLL | - | No Load Losses |
| NOP | - | Normally Open Point |
| PF | - | Power Factor |
| PMT | - | Pole Mounted Transformer |
| SPN | - | South East Power Network |
| THD | - | Total Harmonic Distortion |
| UKPN | - | UK Power Networks |