1. INTRODUCTION

Special condition 2K of SPT’s transmission licence requires SPT to publish an annual transmission losses report detailing the present level of transmission losses and progress on our strategy to minimise transmission losses.

Based on metered data the total losses on the SPT network, i.e. the difference between energy flowing into and out of our network, for the period between 1 April 2014 and 31 March 2015 were 420 GWh\(^1\), representing an operational cost of approximately £25m\(^2\). The following sections of this report discuss a number of factors that have an impact on this number and how it might change in future. It also outlines progress made towards improving the losses-related performance of our network and the impact of new technologies that we are deploying in line with our Transmission Strategy published in December 2013.

2. KEY FACTORS THAT INFLUENCE SPT TRANSMISSION LOSSES

We are observing a number of network trends that will have an impact on losses in the SPT network in coming years. In particular, a significant increase in power flow across our network is expected. Further, the impact of embedded generation and changing load characteristics are also briefly discussed below.

Estimates of how implementing our strategy will help to minimise Transmission Losses on our network have been included throughout this report.

2.1 Increased network power flows

Presently, the losses on the SPT network with winter peak planning transfers are around 133 MW\(^3\). The closure of Longannet Power Station in 2016 contributes significantly to a reduction in this figure to 83 MW by the winter of 2016/17. However, increased renewable generation connections in Scotland lead to increased peak network transfers and therefore to higher losses. This is illustrated in Figure 1, which shows how network power losses are expected to increase with boundary flows in and out of the SPT area.

Note that the peak losses quoted above include losses in generator transformers, which are not owned or maintained by SPT but are included in the model used for analysis. Total transformer losses are 33 MW, of which 11 MW (one third) are generator transformer losses. The remaining losses (about 100 MW) can be attributed to overhead lines, cables and other equipment.

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\(^1\) The level of Transmission Losses from the licensee’s Transmission System, measured as the difference between the units of electricity metered on entry to the licensee’s Transmission System and the units of electricity metered on leaving that system as per licence condition 2K.4 (a).
\(^2\) In assessing the financial value of losses we have assumed £60/MWh, which is the value generally used in our cost benefit analyses.
\(^3\) Last year, we reported winter peak planning losses of 97 MW for 2014/15 and losses of 127 MW were expected for 2015/16. However, significant fluctuations in peak losses can arise due to changing demand and generation background assumptions.
While peak losses are expected to continue to increase as a consequence of the connection of onshore and offshore renewable generation leading to higher bulk power flows, the year-round losses are expected to be substantially below these values, depending on generation patterns, including the impact of smaller embedded generation.

The increase in network power transfers is the largest single contributor to the expected increase in transmission network losses. Losses are proportional to circuit resistance, but also proportional to the square of the current flowing in those circuits. In other words, halving the resistance of a circuit will halve the losses in that circuit, but doubling the current will increase the losses by a factor of four. That means that if it has been possible to halve the resistance in a circuit by using lower-loss conductors and/or increasing the number of conductors in the bundle, a 40% increase in current neutralises the benefit of the reduced circuit resistance.

![Figure 1. Projected impact of boundary transfer on peak SPT network losses.](image)

Against a background of increased network transfers, achieving a reduction in total network losses would not be economic or efficient. However, we are working to reduce the losses associated with each unit of energy transmitted across the SPT network by considering losses and wider environmental impacts carefully when evaluating options for transmission reinforcements or asset replacement. For example, the cost benefit analysis we perform takes account of what can be achieved with options like low loss transformers. This feeds into decisions on network development prompted by asset condition, customer connections or other reasons. In general, the cost of avoided losses alone is unlikely to justify the replacement or upgrading of a circuit or transformer.
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2.2 Increased volume of embedded generation

Large and small embedded generation has the effect of offsetting demand whilst it is generating, normally reducing the current through grid supply transformers and associated feeder circuits. In the SPT area, most embedded generation is renewable with variable output, making it difficult to estimate the network-wide impact on losses. At some grid supply points, the volume of embedded generation is significant and could lead to a power flow from the grid supply point to the transmission network, potentially up to the available capacity limit. In some circumstances this might actually result in higher losses than without the embedded generation. Over the next few years, such conditions are only expected under high-wind conditions and will not exist for extended periods of time.

As embedded generation generally offsets demand, it is expected to lead to a reduction in equivalent grid supply point demand and therefore a reduction in grid supply point transformer losses.

2.3 Changes in load characteristics

Over the next few years, a substantial reduction in reactive power demand at grid supply points is predicted. In the SPT area, 90% of grid supply points currently have a power factor of 0.95 or better. By 2020, this is expected to improve to the extent that 90% of grid supply points will have a power factor of 0.98 or better. This improvement in power factor leads to a small reduction in current and therefore a small reduction in losses4, mainly associated with transmission feeders and grid supply point transformers.

In combination with embedded generation, the pattern of load on the network determines the time profile of power that is carried on the transmission network. Given that losses are proportional to the square of the current, a ‘peaky’ profile will result in more losses overall than a ‘flat’ profile that delivers the same amount of energy. Thus, changes in load, or embedded generation, that result in higher peaks in power transfer even if total energy transfer remains the same, will result in higher losses. The overall load profile shape is outside of the control of SPT but is another factor that influences losses on our network.

3. THE IMPACT OF ASSET REPLACEMENT

3.1 Transformers

When procuring transformers, we consider an estimate of the total cost of ownership in order to determine the most economic purchase. This evaluation recognises both the purchase price of the

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4 Assuming constant active power, this change in power factor leads to a load current reduction of about 3%. Losses are proportional to the square of the current. For example, a transformer with a load loss of 50kW at 0.95 power factor, will have losses of 47kW if the power factor of the load is improved to 0.98; a reduction of 6%.
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transformer and the transformer losses, by capitalising the cost of these losses over the expected life-time of the transformer.

During 2014/15, a number of transformers in our network were replaced. Modern transformers have considerably lower losses when compared to transformers that have been in service for many decades. As an example, consider Portobello SGT2A (120 MVA, 275/33 kV). The old transformer was manufactured in 1961. It had no-load losses of 85 kW and an equivalent short-circuit resistance of 0.6% on a 120 MVA base. The new transformer has no-load losses of 46.2 kW and a short-circuit resistance of 0.417%.

Although the no-load losses are reasonably constant while the transformer is energised, the load losses are a function of the transformer loading. By considering the loading of the transformer for one year before it was replaced, a comparison of losses associated with the old and new transformers is possible. Based on actual loading, it is estimated that the old transformer dissipated 1055 MWh over the year before it was replaced. Assuming a cost of £60/MWh, this amounts to an annual cost of £63.3k.

Assuming that the new transformer will be subjected to exactly the same loading pattern over its first year of service, it is estimated to dissipate a total of 620 MWh at a cost of £37.2k. Therefore, the new transformer represents an annual saving of around £26.1k in operational costs due to avoided losses.

A similar analysis has been carried out for a number of recent and ongoing transformer replacements. The results are summarised in Table 1.

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5 Appendix A-20 of Specification for Transmission System Double Wound Transformers (TRAN-03-022, Issue No. 7) and Specification for Transmission Autotransformers (TRAN-03-024, Issue No.5).

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Table 1. Transformer losses

<table>
<thead>
<tr>
<th>Transformer</th>
<th>Losses of old transformer in year before replacement (MWh)</th>
<th>Equivalent losses of new transformer (MWh)</th>
<th>Approximate annual cost saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portobello SGT2A 120 MVA 275/33 kV</td>
<td>1055</td>
<td>620</td>
<td>£26.1k</td>
</tr>
<tr>
<td>Whitehouse SGT1 120 MVA 275/33 kV</td>
<td>853</td>
<td>376</td>
<td>£28.6k</td>
</tr>
<tr>
<td>Sighthill SGT1 120 MVA 275/33 kV&lt;sup&gt;6&lt;/sup&gt;</td>
<td>1189</td>
<td>469</td>
<td>£43.2k</td>
</tr>
<tr>
<td>Easterhouse SGT1 120 MVA 275/33 kV</td>
<td>765</td>
<td>443</td>
<td>£19.3k</td>
</tr>
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<td>Bonnybridge T1 90 MVA 132/33 kV</td>
<td>391</td>
<td>255</td>
<td>£8.2k</td>
</tr>
<tr>
<td>Bonnybridge T2 90 MVA 132/33 kV</td>
<td>566</td>
<td>333</td>
<td>£14.0k</td>
</tr>
</tbody>
</table>

3.2 Overhead lines

A number of circuit re-conductoring projects are currently in progress. On the YW route, re-conductoring of the Dalmally – Windyhill 275 kV circuit has been completed. The previous twin Zebra (400 mm² ACSR) bundles were replaced by twin Totara (425 mm² AAAC) bundles. Using a similar approach as for transformers in the previous section, the reduction in losses can be demonstrated by aggregating the circuit losses over a year of operation.

The Dalmally – Windyhill 275 kV circuit is 79 km long and had a resistance of 2.71 Ω before re-conductoring. After upgrading, the total circuit resistance is reduced to 2.42 Ω. Over a recent annual cycle of operation, and before re-conductoring, the circuit dissipated a total of 2033 MWh. For the same load cycle, the upgraded circuit has a total loss of 1820 MWh. At £60/MWh, these values represent costs of £122.0k and £109.2k respectively. Based on a like-for-like load cycle, the new conductor is expected to save approximately £12.8k in annual costs.

3.3 Shunt reactors

Similar to transformers, when procuring shunt reactors, we establish the total cost of ownership in order to determine the most economic purchase. This evaluation recognises both the purchase price of the reactor, as well as reactor losses, by capitalising the cost of these losses over the expected life-time of the asset.

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<sup>6</sup> Sighthill SGT1 has been replaced by a 180 MVA unit with two 33 kV secondaries rated at 90 MVA each.
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We are in the early stages of replacing a number of shunt reactors on our network and the need for a number of additional reactors has been identified. Although losses in these devices are unavoidable, we aim to minimise these as far as economically possible. We are also considering the use of air-cored reactors, which do not have an iron core and therefore do not exhibit the associated iron losses. Our existing 33 kV, 60 MVar shunt reactors were installed in the mid-1960s and typically have losses of 240 kW when energised. Present indications are that modern shunt reactors of a similar rating will have losses in the order of 180 kW. Note that shunt reactors are only likely to be in service during relatively light-load system conditions to limit excessively high voltages. Therefore, the duration for which shunt reactor losses are present on the system will be limited, unlike a transformer which always presents at least a no-load loss.

4. NEW TECHNOLOGIES

4.1 Series compensation

In 2013, we awarded a contract for four series capacitor installations on the Anglo-Scottish interconnector circuits. This project is currently nearing completion. Tenders were evaluated on a whole-life cost basis and losses were included in this calculation. Tenderers were required to submit a detailed loss calculation report, considering a range of operating conditions and the impact of component tolerances. For tender evaluation, the losses at 50% load and nominal component values were used, as this was considered a realistic operating point for comparison on an intact network.

We are constructing fixed series capacitors with passive bypass filters for sub-synchronous resonance mitigation. The losses in these installations are more susceptible to changes in system frequency and variations in component tolerances than competing technologies such as thyristor controlled series capacitors. However, under normal operating conditions, the losses were assessed as being lower than those of alternative options.

The final tender evaluation involved careful consideration of the sub-synchronous resonance risks, balanced against cost, a high availability requirement, losses and environmental impacts such as noise emission. The losses of the winning bid were assessed as approximately 70 kW per installation lower than the nearest competitor. These losses led to a difference in whole-life cost contributions in the order of £100k per series compensation installation.

Note that when the series capacitors are not required for network operation, i.e. at time of lower power transfer, they will be switched out (by closing a bypass circuit breaker). Although this is primarily an additional sub-synchronous resonance mitigation measure, it also eliminates losses from the series compensation equipment during such periods. An estimate of this out-of-service time was included in the calculation of the cost of losses.

It is important to understand that the series capacitors do not have a direct impact on the losses associated with the circuits in which they are installed. Although series compensation has the effect of reducing the overall circuit impedance, the resistance of the conductors remains unaffected. Actually, series compensation allows higher transfers on the existing interconnector circuits, which will in turn lead to higher losses in these circuits. However, this has to be considered against a backdrop of an increase of 1100 MW in the capability of the Anglo-Scottish interconnector.
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interconnectors, which leads to increased utilisation of renewable forms of generation and a considerable reduction in constraint costs associated with these circuits.

4.2 Shunt capacitors

Between 2013 and 2015, we have installed mechanically switched capacitors with damping networks (MSCDNs) at Windyhill, Longannet\(^7\), Elvanfoot, Moffat and Cockenzie\(^8\) with a combined rating of 1275 MVar. These devices are switched in and out as required operationally for voltage control or to support the system after a fault. In most cases, the MSCDNs will not be in service for extended periods of time, which helps to minimise power losses from these devices.

The losses in an MSCDN broadly arise from two sources: fundamental frequency (50 Hz) losses and losses due to the presence of harmonic voltages on the network. Under ideal conditions, the losses associated with a MSCDN are not very high, but the 50 Hz losses could rise to over 100 kW per installation due to changes in system frequency or due to component tolerances. Harmonic voltages can lead to significant losses in the damping resistors of MSCDNs. It is difficult to quantify the harmonic losses as harmonic voltages on the network vary considerably. In fact, switching the MSCDN in or out of service will have an impact on the harmonic voltage levels. Under worst-case conditions, the losses in the damping resistor could rise to several hundred kW.

When we have gained further operational experience with MSCDNs we will be in a better position to estimate the total losses from these devices. This will involve determining a realistic duty cycle and direct measurement of the harmonic voltages that are typically present when the MSCDN is energised. If the losses are found to be significant, we will report this in future years.

Note that the design of MSCDNs has been standardised to the point where an evaluation of losses at tender stage does not have an impact on the choice of supplier. The variation between suppliers is minimal, depending only on small component-level variations.

4.3 Western Link HVDC interconnector

The Western Link HVDC interconnector is currently under construction. The link will interconnect Hunterston in the SPT area to Deeside in the National Grid transmission area and has a rated capacity of 2250 MW. When operating at rated current, the total losses of the link are in the order of 45 MW, which is significantly lower than the losses of an equivalent AC circuit of the same capacity and length. This includes losses in both converters and in the DC cable, but does not include losses in the harmonic filters or the SVC that will be installed at Hunterston as part of this project. It is difficult to predict the total losses of the link, e.g. over a year of operation, as these will depend on the operating point of the link, the operating point of the SVC and the number of harmonic filters and/or reactors switched in.

The Western Link is being designed to minimise losses over and above the loss reduction that can be achieved by using HVDC technology instead of an AC interconnector. A good example is if the

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\(^7\) Two MSCDN’s are installed at Longannet, but only one has been fully commissioned, the other is expected to be commissioned by January 2016.

\(^8\) The Cockenzie MSCDN is expected to be commissioned in January 2016
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HVDC station control system detects that a shunt reactor and a harmonic filter (that is not required for harmonic performance) are switched in at the same time, it will switch out both devices to reduce losses. Although the reactive power control system will primarily control harmonics and system voltage, it will manage losses if there is an opportunity to do so.

When we have gained further operational experience on the Western Link and have had an opportunity to assess the resulting changes in power flow on our AC network, we will report on the impact of the Western Link on system losses in further detail.

5. SUBSTATION AUXILIARY SUPPLIES

The power supplies to our substations (for protection and control equipment, battery chargers, cooling systems, lighting, heating, etc.) are usually derived from secondary windings on 33 kV neutral earthing transformers. Presently, these supplies are not metered and substation demand, which is a transmission loss, is therefore not accounted for separately. Most equipment at substations is essential and could not be switched off. However, it may be that lighting and room heating for example, could be better controlled. We aim to identify where efficiencies can be made through energy saving measures and will implement these where it is cost effective to do so.

In 2014 we reported that we were planning a pilot project to install energy metering at a small number of test sites and to carry out an audit of possible on-site energy-saving measures. This would indicate if the cost of installing energy metering at all our transmission substations would justify the cost savings and environmental benefits that could be obtained by monitoring the energy consumption of each site more carefully. We are currently discussing the project with a number of potential contractors and are planning to start this work early in 2016.

6. OTHER IMPACTS

As described above, for a given flow of power, the reduction of losses implies a reduction in series resistance of equipment or an increase in shunt resistances, such as the no-load losses of transformers. This has two important side-effects:

1. The time constant associated with the DC component of fault currents is increased, leading to more onerous circuit breaker duties. This is particularly significant at many SPT grid supply points, where the fault current is dominated by the characteristics of the grid supply transformers. Here, a reduction in transformer losses increases the DC fault current component time constant to values in excess of the standard value, necessitating the use of higher-rated circuit breakers than normal. The issue is exacerbated by increased volumes of embedded generation, which also contribute to increased fault levels. However, our view is that the deliberate use of transformers with high load losses to counter this problem is not justifiable or in line with our sustainability strategy. We will therefore continue to strive to minimise transformer losses and are employing and investigating other methods to manage system fault levels.
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2. A second impact of reduced system losses is the reduction in damping that is available to higher-frequency phenomena such as harmonics or switching transients. The implication is that harmonic resonances are more pronounced and that oscillating transients take longer to decay. At this time, we do not have evidence that this is an increasing problem. However, increased harmonic levels themselves lead to increased losses, e.g. in MSCDNs as explained above or due to losses caused by harmonic currents flowing in circuits and equipment. In the longer term, changes in load characteristics (e.g. due to the increasing use of power electronic equipment) will also have an impact on system harmonics. We continue to keep our harmonic modelling techniques under review and also rely increasingly on direct measurements to manage harmonic levels on our network.

7. CONCLUSION

We are committed to reducing losses on our network wherever and however it is economic and efficient to do so. As we continue to connect more renewable generation in Scotland we are working toward getting the most out of our existing assets and increasing the capacity of our network to accommodate this generation. At the same time, we are also aiming to improve the overall performance of our network. This includes careful consideration of losses and minimising these as far as possible in a way that balances capital investment, operational cost and environmental impact. We will continue to analyse, monitor and record losses to demonstrate how our decisions are helping to reduce losses and thereby serving our customers better.