Engineering Justification Paper – Harmonic Filters				
Name of Scheme/Programme	Harmonic Filters			
Primary Investment Driver	Compliance with Harmonic Standards (ER G5/4)			
Scheme reference/ mechanism or category	SPT200126 SPT200127			
Output references/type	LRT2SP2049			
Cost	£24.235m			
Delivery Year	2022 - 2026			
Reporting Table	B0.7 Load Master Data B4.2a Scheme Summary B4.5 Scheme Asset Data B4.5a Scheme Asset Data			
Outputs included in RIIO T1 Business Plan	No			
Spend apportionment	**Scheme**	**T1**	**T2**	**T3**
	SPT200126/7	£0.236m	£23.999m	£0m

Issue Date	Issue No	Amendment Details
July 2019	Issue 1	First issue of document
December 2019	Issue 2	Updated monetary values, sections 4.3 and **Error! Reference source not found.** added and minor edits and corrections.

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1 Introduction

The installation of harmonic filters is required at Linnmill, Moffat, New Cumnock, Black Hill, Margree and Newton Stewart to prevent voltage harmonics in excess of planning and compatibility limits in the Coalburn, Moffat and south-west Scotland 132 kV networks.

This paper supports a proposal to install the same standardised filter design at all locations at 132 kV. This is a 20 MVAr damped filter, similar to an MSCDN[1] or also known as a C-type filter.

At some sites, the risk of harmonic problems is higher or high harmonic levels have already been reported. To maximise the impact of the harmonic filters, they should (as far as possible) be installed in the following sequence:

1. Black Hill
2. New Cumnock
3. Newton Stewart
4. Margree
5. Moffat
6. Linnmill

This paper should be read in conjunction with Annex 21 – Strategic Investment Plan for Load which explains the interaction of this scheme with others in the load related plan.

2 Background Information

An increasing number of large windfarms are being connected to relatively weak 132 kV networks such as those in south-west Scotland or the Coalburn 132 kV network. These networks are also characterised by the increased use of long underground cable circuits. The combination of a relatively high source impedance with higher cable capacitance leads to lower resonant frequencies in the network, typically below the 20^{th} harmonic (1 kHz). There is therefore a high risk that a network resonance coincides with a background harmonic, leading to harmonic voltages above planning and compatibility limits.

2.1 Harmonic Compliance

Users are normally responsible for harmonic compliance at their connection point. This is based on the premise that harmonic voltages at the connection point are primarily due to harmonic injection from the User's plant, e.g. in the case of a HVDC converter. In such cases, the User can install harmonic filters to limit the harmonic injection to acceptable limits.

The harmonic injection from most modern wind turbines is very low and high harmonic voltages at the connection point arise primarily due to harmonics that already exist on the network, amplified by a resonant condition. For such resonant conditions, the harmonic levels at the connection point are a strong function of the network characteristics, making it very difficult for a User to design harmonic mitigation:

[1] Mechanically Switched Capacitor (bank with) Damping Network. Equipment primarily designed as shunt capacitor for reactive compensation, but with an additional damping network to mitigate potential harmonic resonance, typically rated 150 Mvar (275 kV) or 225 Mvar (400 kV)

1. The final network design is uncertain. The resonant frequencies of the network will move as network conditions change and as the network is developed and new connections are made.
2. The design of future windfarms and their harmonic emissions are unknown.
3. Network outages (due to faults or for maintenance or construction) can have a significant impact on harmonic resonance.
4. Mitigation designed by a User to deal with harmonic resonance is unlikely to be efficient from a whole-system point of view.
5. Harmonic resonances do not only affect windfarm connection points but lead to increased harmonic voltages throughout the network. The best location for a harmonic filter may not be at the connection point, but elsewhere in the transmission network.
6. Windfarm array cables contribute to the problem. However, high harmonics are due to the amplification of pre-existing background harmonics and generally not harmonics produced by windfarms.

From a whole-system point of view, it is therefore more economic and efficient for SPT to design and install harmonic mitigation, as proposed by two SPEN innovation projects [1, 2, 3]. Note that we are also collaborating with National Grid TO, who are also considering this approach in relation to the connection of large offshore windfarms, rather than onshore connections to a relatively weak 132 kV network[2].

This approach also solves a number of problems:

1. Harmonic headroom in the network can be managed better and apportioned more fairly.
2. Mitigation costs are distributed more equitably between Users. E.g. a situation where windfarm B avoids filter installation costs because windfarm A nearby has already installed filters becomes much less likely.
3. Reduces the risk of late detection of harmonic problems.
4. Improves filter redundancy. E.g. a coordinated approach would avoid extensive harmonic problems arising from the failure or unavailability of a single harmonic filter bank. Note that disconnecting the associated windfarm would not necessarily solve the problem.

2.2 Allocation of Costs

As outlined in the previous section, Users are normally responsible for harmonic mitigation and therefore the full cost of mitigation. For Users that are significant sources of harmonic emissions, this is consistent with a “polluter pays” approach. However, most windfarms are not a significant source of harmonics, i.e. they are not by themselves polluters. In some parts of the SPT 132 kV network, they simply form part of a wider resonant system that amplifies background harmonics caused by a range of sources, including consumer devices and equipment. This suggests that part of the cost of harmonic mitigation should be socialised, rather than penalising individual Users for resonant conditions that are largely out of their control.

[2] NIA_NGTO018 (Harmonic compliance management), see https://www.smarternetworks.org/project/nia_ngto018

2.3 Proposed Approach

It is anticipated that the harmonic filter installations proposed in this paper will be funded fully via the RIIO-T2 price review.

However:

1. The responsibility for harmonic compliance should not be removed from Users to ensure that they remain liable if they connect polluting equipment to the network.
2. User choice could have a significant impact on harmonic resonance, e.g. the use of cable instead of an overhead line connection. In such cases, where there is deemed to be an increased risk of harmonic resonance, a harmonic filter should be included in the offer as a one-off cost.

This approach remains consistent with the "polluter pays" principle while ensuring that harmonic compliance is managed in an economic and efficient manner across the transmission system.

We have engaged with various stakeholders about our approach and there has been strong support for SPT taking a more active and whole-system role in the management of voltage harmonics. Although the responsibility for compliance will remain with Users, our approach reduces the risk of non-compliance

3 Optioneering

The table below presents a summary of the options considered for this project.

	Option	Status	Reason for rejection
(a)	No Intervention	Rejected	This would lead to increasing harmonic levels on the transmission network, causing a disturbance to Users and transmission equipment. Due to resonant conditions, harmonic levels are likely to exceed the ER G5/4[3] [4] compatibility levels.
(b)	Windfarm filters only	Rejected	This is the existing approach and as discussed in section 2, is not economic or efficient from a whole-system point of view. Further, it will not eliminate excessive harmonic voltages in all areas of the network.
(c)	33 kV standard filters	Rejected	This is a variation of the previous option, i.e. installing a standardised filter at windfarm 33 kV connection points. This would lead to the installation of a high number of filters (between 15 and 20 installations), but these would not be effective in controlling harmonic voltages in all areas of the network. This option was considered in detail in NIA project NIA_SPT_1506 [1, 2].
(d)	132 kV standard filters	Proposed	Costs have been obtained for this option and it is considered in further detail below. This approach was shown to provide the best technical solution, able to mitigate harmonic levels in

[3] Engineering Recommendation G5/4 has been updated to G5/5 and consequent changes to the Grid Code and Distribution Code are currently under consideration by Ofgem (November 2019). Although ER G5/5 slightly increases planning and compatibility limits for some harmonics, this does not have a material impact on this project, where resonant conditions can lead to harmonic voltages far in excess of the compatibility levels.

			the 132 kV network in an economic and efficient manner by NIA projects NIA_SPT_1506 [1, 2] and NIA_SPT_1610 [3].
(e)	Active filters	Rejected	This option uses power electronic converters and a suitable control system to provide harmonic filtering. This technology is often deployed as part of e.g. a STATCOM, i.e. a system that provides reactive compensation and harmonic filtering. The capital and operational costs are very high and the technology is effective only at low harmonic orders. Further, availability is likely to be significantly lower than that of a passive filter and losses and noise emissions are high.
(f)	Bespoke filter designs for each location	Rejected	The 132 kV filters proposed in d) are a standardised design that provides damping across the full range of harmonic frequencies. This ensures a high level of immunity to e.g. outages or network changes. It would be possible to design more bespoke filters for each location, which would provide more efficient filtering at specific harmonics with a reduced filter rating. However, such filters could themselves become part of an unintended resonant condition, would be very sensitive to network changes and may require re-tuning or extension in future. Further, the use of a standard design should achieve efficiencies in procurement, delivery, spares holding, etc.

Of these, only option d) has not been rejected and therefore this paper only considers this option in detail. As only one technical option is deemed to be efficient, a CBA has not been provided to support this decision.

4 Detailed Analysis

4.1 Damped Harmonic Filters

The proposed schematic of the harmonic filter installation is shown in Figure 1. This is a 132 kV, 20 Mvar design. One of the main advantages of the proposed filter design is that it provides damping to a wide range of harmonic frequencies, rather than being sharply tuned to a specific harmonic. This characteristic is important for this project, but comes at the expense of increased losses.

Insulation coordination has to be considered in further detail, but note that a high-energy surge arrester is likely to be required across the resistor. The switching duty for the associated circuit breaker is not unusually onerous and a standard 132 kV circuit breaker rated for capacitive switching duty can be employed.

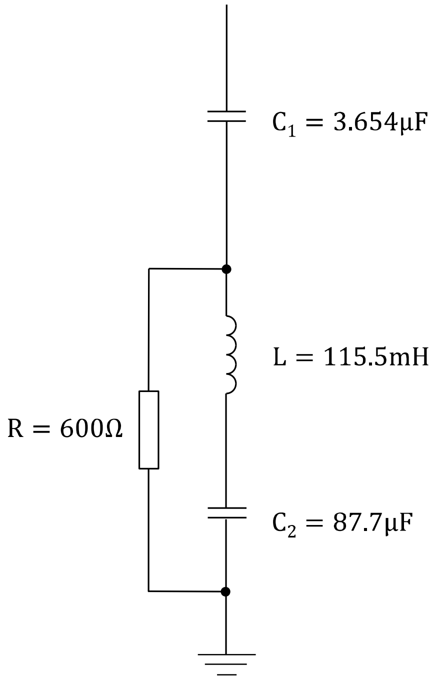

Figure 1. Proposed harmonic filter.

4.2 Losses

Ideally, no 50 Hz current flows through the filter resistor (R in Figure 1)[4], which means that the 50 Hz losses are normally very low. In practice, some losses result due to component tolerances or deviation of the system frequency from 50Hz. The filter losses due to harmonic currents depend on the levels of harmonic distortion on the network. If it is assumed that all harmonic voltages are at the maximum compatibility limit allowed by ER G5/4, the losses could be in excess of 500 kW. However, such a condition is extremely unlikely to arise and would not persist for very long. Losses are normally not expected to exceed 60kW – 70kW.

Generally, lower harmonic voltage levels across the network will reduce losses at harmonic frequencies and therefore contribute to a reduction in total network losses. However, extensive network simulations are required to estimate these losses. As harmonic losses are low compared to 50 Hz losses, this has not been attempted.

4.3 Filter Costs

As SPT has not previously installed harmonic filters, the filter costs have been estimated based on engagement with suppliers and experience from MSCDN installations, although the latter are connected at higher voltages and have a significantly higher rating. Note that the filter components (Figure 1) account for only around 10% of the total cost, the remainder arises from substation extensions, switchgear, engineering and installation. In many cases, the ground preparation costs are increased by the presence of peat due to these being remote sites.

4.4 Cost Benefit Analysis

A cost benefit analysis was not carried out for this project as only one option met the requirements. The installation of harmonic filters also has the added benefit of contributing to the faster connection of new renewable generation while maintaining harmonic voltages within limits, which

[4] L and C_2 are tuned to 50 Hz to bypass the resistor.

benefits all connected customers and consumers. The connection process is improved because the risk of harmonic non-compliance, or the late discovery of non-compliance, is reduced for windfarm developers, while providing improved and more economic and efficient whole-system management of harmonics.

5 Conclusion

Our analysis shows that the installation of harmonic filters at strategic locations on 132 kV networks provides the most economic and efficient solution, from a whole-system point of view, to the harmonic resonance problems that are emerging in our network. This project enables system operation with very high levels of renewable generation, thus contributing directly towards the achievement of Net Zero.

We recommend that six new harmonic filters are installed in the SPT network as outlined above as part of our RIIO-T2 works.

6 Future Pathways – Net Zero

Primary Economic Driver

The primary driver for this investment is technical compliance with the engineering standard ER G5/4. The solution acts as a further enabler of future generation across the SPT network by mitigating some of the issues which are arising.

Payback Periods

This solution is required for technical compliance therefore a payback period has not been considered.

Pathways and End Points

This solution is justified in all Future Energy Scenarios. We anticipate that the issue of harmonics will continue to increase due to network changes (e.g. increased use of underground cables) and as further power electronic devices connect onto the GB electricity system.

Asset Stranding Risks

We do not consider there to be a risk of asset stranding in any of the future scenarios. We expect that going forward, further filters may be required in the RIIO-T3 period as more issues emerge from changing generation and demand patterns.

Sensitivity to Carbon Prices

This scheme is not sensitive to carbon price changes.

Future Asset Utilisation

It has been assessed that the preferred option is consistent with the future generation and demand scenarios and that the risk of stranding is very low. The harmonic filters are intended to be in permanent operation and will only be out of service to facilitate maintenance or other access. Utilisation is therefore expected to be near 100% for the life of the equipment.

Whole Systems Benefits

The proposed approach has been discussed with generation customers and other directly connected customers to ensure that it meets their needs as well as those of the transmission network. The proposed approach may have further whole system benefits by offsetting the requirement for some future customers to install harmonic filters as this approach provides higher utilisation and coordination than individual solutions at generators point of connection.

7 Supporting Documentation

1. WSP Parsons Brinckerhoff, "Development of a Standard 33kV Harmonic Filter – Stage 1", June 2016. (NIA project NIA_SPT_1506, Development of a Standard 33kV Damped Harmonic Filter Design.)
2. WSP Parsons Brinckerhoff, "Development of a Standard 33kV Harmonic Filter – Stage II", February 2017. (NIA project NIA_SPT_1506, Development of a Standard 33kV Damped Harmonic Filter Design.)
3. Electric Power Research Institute (EPRI), "South West Scotland Harmonics Study – Filter Design and Analysis Results", July 2017. (NIA project NIA_SPT_1610, Innovative Approach for Transmission Harmonics Issues.)
4. Engineering Recommendation G5/4-1, "Planning Levels for Harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the United Kingdom", October 2005.