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Standard passive harmonic filter for wind farm connections

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Abstract: The design of harmonic filters required for harmonic voltage compliance depends on the characteristics of the network, which are usually not exactly known and are subject to uncertainties. Network conditions may change considerably from those that a harmonic filter was originally designed for. This study proposes a methodology to determine a standard harmonic filter design which can be deployed for the majority of network conditions in order to comply with the harmonic voltage distortion requirements of the grid code.

1 Introduction

An increasing number of power electronic converter driven generators are being connected via long cable circuits. This type of connection often leads to resonant conditions that result in amplification of existing background harmonic voltage distortion. This effect is often deteriorated by extensive wind farm cabling.

Before a connection offer is made, network operators carry out harmonic voltage distortion assessment to evaluate the connection against standard harmonic voltage distortion requirements. The outcome of this assessment may suggest harmonic mitigation solutions, which should be in place before connection takes place.

At the time when a connection offer is made, not enough information is available about the length and type of cable circuit, the wind farm layout or the characteristics of future adjacent connections. In addition, other uncertainties such as different network outages, demand variations and possible future network expansions need to be considered for harmonic assessment. These uncertainties and lack of information can turn design of suitable harmonic mitigation solutions very difficult, or extensive harmonic studies may be required.

A solution to aforementioned issues is to deploy a standard passive harmonic filter that can be a harmonic mitigation solution for the majority of network conditions and wind farm layouts. SP Energy Networks (SPEN), one of the transmission network owners and distribution network operators in the UK, which deals with a large number of wind farm connections, has investigated the feasibility of a standard passive harmonic filter.

The aim of this paper is to present the methodology and assumptions used to develop a standard passive harmonic filter scheme, which can be proposed at the very early stage of connection offer. In this way, all the financial and technical risks to the developers and the network operator can be reduced when connection offer is made.

2 Network model

A radial network arrangement which includes the connections from the 400 kV grid supply point (GSP) to the 33 kV point of connections (PoC) was considered for developing and checking the performance of the standard harmonic filter. This network arrangement, which is shown in Fig. 1, is a typical arrangement for connection of wind farms. It was assumed that three wind farms can be connected to this network at different stages.

The elements of network model are as follows:

Voltage source: a Thevenin harmonic voltage source behind a frequency-dependent impedance. This represents the background harmonic voltage distortion at 400 kV network.

Cable circuit: a 132 kV 1600 mm^2 XLPE Al cable circuit dedicated for connections of wind farms to the GSP.

GSP TX1, GSP TX2, and GSP TX3: typical 240 MVA 400/132 kV transformers.

TX1, TX2, TX3: typical 90 MVA 132/33 kV transformers.

C1, C2 and C3: capacitance representing equivalent wind farm cable array capacitances.

A standard harmonic filter should be suitable for different network conditions, so it was assumed that the aforementioned network parameters are subject to some variations as shown in Table 1. The variations of network parameters introduce different network scenarios, causing varying network harmonic resonances and leading to changing harmonic voltage distortion levels.

3 Harmonic compliance requirement

UK ENA Engineering Recommendation (ER) G5/4 [1] provides harmonic voltage distortion planning levels and compatibility levels at transmission and distribution voltage levels. The planning levels are used by UK network companies as reference levels when network's harmonic distortion levels are assessed for connection of a customer (load or generator).

In addition to the planning levels, ER G5/4 also includes compatibility levels that are aligned with the IEC 61000 series standards [2] and, depending on the voltage level, are either higher or equal to the planning levels.

In certain cases it may well be worth considering the use of compatibility levels rather than the planning levels for the acceptability of a particular connection on the basis of designing the most economical system. This can be a dedicated line to supply a particular installation only or alternatively there may be no other connection that can be affected by the emitted harmonics.

The overall harmonic voltage distortion largely depends on the network harmonic impedance and the background harmonic distortion in the network. Depending on the network characteristics, the background distortion may be amplified at

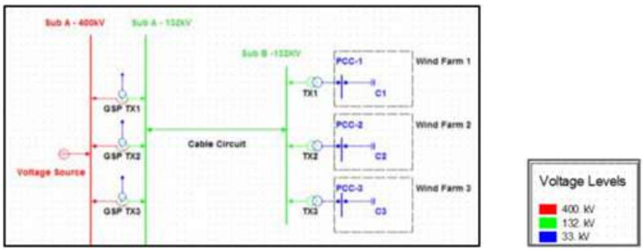

Fig. 1 *Network model*

Table 1 Network parameter variations

Network component	Variation range
cable circuit length	from 1 to 30 km, step change
C1,C2,C3	0.3–2.1 MVAr, step change
GSP TX1, TX2, TX3	in service or out of service
TX1, TX2, TX3[a]	in service or out of service

[a]This variation is to model the number of wind farms connected to the network.

different locations of the network. In this study, as a standard harmonic filter needs to be suitable for the majority of network conditions and harmonic background levels, the effectiveness of a standard harmonic filter is assessed based on the change in harmonic distortion gain factors (HDGFs). These gain factors directly relate to how the background harmonic voltage distortion is amplified or attenuated throughout the network for the individual harmonic orders.

In the context of this study, HDGF is defined as the resultant harmonic voltage distortion level at any node of the network (Fig. 1) following the application of 1.0 p.u. voltage at the 400 kV busbar (Sub A-400 kV) for each individual harmonic order.

The following assumptions have been made for permissible HDGFs at different voltage levels considering 50% ER G5/4 planning level headroom at the 400 kV node:

- The permissible HDGF at the 400 kV node was calculated to be 2.0 for all harmonic orders.
- The permissible HDGF at 132 kV nodes is assumed to be 3.0 for all harmonic orders.
- The permissible HDGFs at 33 kV nodes should maintain the 33 kV voltage harmonic distortions within 75% of the compatibility levels.

Table 2 shows the permissible HDGFs assumed in this study.

4 Location and types of passive harmonic filters

It was assumed that a standard harmonic filter solution can be one of the following filter types: single tuned, double tuned, C-type. The preferred location for a standard filter solution would be at the customers' site where any new customer can deploy standard filter blocks to comply with harmonic distortion requirement. Nonetheless, a filter block at 132 kV can have a significant impact on reducing the harmonic distortion amplification at the 33 kV network. Therefore, PoCs (33 kV nodes) and the 132 kV node (Sub – B 132 kV) are assumed to be possible locations for connection of a standard harmonic filter.

5 Methodology

The main challenge for finding a suitable standard harmonic filter solution is to search an extensive number of scenarios containing different network conditions and harmonic filter arrangements.

In order to decompose the search space and effectively find the solution, a four-step methodology (see Fig. 2) was established and executed as follows:

Step I – establish extent of issue

- Create network scenarios considering the variation of network parameters within the ranges defined in Section 2-A.
- Calculate HDGFs at different voltage levels for all network scenarios.
- Determine the spread of HDGFs and identify worst-case network scenarios.

Step II – data clustering

- Carry out data analysis and clustering of network conditions based on the HDGFs calculated for highly problematic harmonic orders.
- Determine the probability of each network cluster and identify a representative network condition for each cluster.

Step III – Filter optioneering

- Create filter scenarios considering different locations, types and filter parameters – a large number of filter scenarios was considered.
- Re-calculate HDGFs for the representative network conditions considering different filter scenarios.
- Considering filter scenario impacts on representative network conditions, identify possible filter options, which can maintain the

Table 2 Permissible HDGFs

Harmonic order	33 kV	132 kV	400 kV	Harmonic order	33 kV	132 kV	400 kV
2	3.00	3.00	2.00	22	2.73	3.00	2.00
3	5.00	3.00	2.00	23	4.22	3.00	2.00
4	1.88	3.00	2.00	24	2.66	3.00	2.00
5	4.50	3.00	2.00	25	3.82	3.00	2.00
6	1.50	3.00	2.00	26	2.60	3.00	2.00
7	5.00	3.00	2.00	27	1.50	3.00	2.00
8	1.88	3.00	2.00	28	2.54	3.00	2.00
9	4.50	3.00	2.00	29	3.47	3.00	2.00
10	1.88	3.00	2.00	30	2.50	3.00	2.00
11	5.25	3.00	2.00	31	3.31	3.00	2.00
12	3.44	3.00	2.00	32	2.46	3.00	2.00
13	4.50	3.00	2.00	33	1.50	3.00	2.00
14	3.21	3.00	2.00	34	2.43	3.00	2.00
15	2.00	3.00	2.00	35	3.01	3.00	2.00
16	3.05	3.00	2.00	36	2.40	3.00	2.00
17	6.00	3.00	2.00	37	2.88	3.00	2.00
18	2.92	3.00	2.00	38	2.37	3.00	2.00
19	5.28	3.00	2.00	39	1.50	3.00	2.00
20	2.81	3.00	2.00	40	2.34	3.00	2.00
21	2.25	3.00	2.00	—	—	—	—

HDGFs within the permissible levels – a small number of filter scenarios was considered.

Step IV – filter selection

- Calculate HDGFs for all network scenarios created in Step I with filter options identified in Step III connected.
- Determine the effectiveness of each filter option and the probability of maintaining HDGFs within the permissible levels.
- Process the final results and recommend a filter option as the standard filter that can be deployed for the majority of network scenarios.
- Define the operational boundaries of the standard filter and where it can be most effective.

6 Results

6.1 Step I – establish extent of issue

The first step was to determine the variation range of HDGFs, considering an extensive list of network scenarios. This also allowed identification of the worst-case network conditions where maximum harmonic resonances may occur.

As explained previously, it was assumed that each network parameter may vary within a range given in Table 1. Taking into account network parameter variations, 107,703 different network scenarios were created. Harmonic analysis was carried out for each network scenario and HDGF values were calculated for different nodes of the network for each individual harmonic order.

The results for some of the odd harmonics are shown in Table 3. The results show that in the majority of cases and at all voltage levels the HDGFs are much larger than the permissible HDFGs. The aim in the next stages is to identify a harmonic filter scheme, which can bring the HDGFs within the permissible levels.

6.2 Step II – data clustering

The purpose of data clustering is to identify network conditions, which may result in similar frequency sweeps or more specifically similar resonance frequencies. Clustering the network conditions provides an insight into possible network frequency resonance behaviours, finding representative network conditions for each cluster, and thus reducing the number of network scenarios, which should be considered for filter optioneering analysis. Following analysis have been carried out:

- The *K*-means method [3] has been used for clustering the network conditions based on the HDGF values.
- In each cluster, a network condition, which is the closest to the average HDGFs variation in that cluster is selected as representative of that cluster.

In order to reduce the size of problem, only highly problematic harmonic orders (5, 7, 11, 13, and 17) have been included in the clustering process. The network conditions have been grouped in 25 clusters based on their HDGFs at aforementioned harmonic orders. The results of the clustering analysis are shown in Fig. 3.

Table 3 Maximum HDGFs for odd harmonic orders HDGF

Harmonic order	At PCC-1 33 kV	At sub B-132 kV	At sub A-400 kV
3	1.78	1.75	1.10
5	44.32	41.13	2.97
7	71.04	60.86	3.73
11	241.41	160.70	7.55
13	222.97	147.35	18.45
15	47.07	24.30	3.72
17	177.09	82.21	8.95
19	88.42	29.80	2.02
23	257.01	70.97	8.41
25	141.86	64.35	9.05

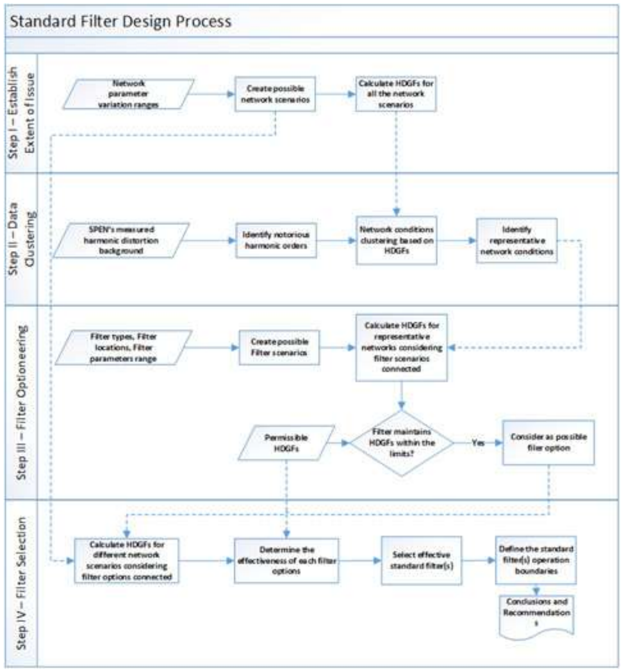

Fig. 2 *Developed methodology for evaluating the feasibility of a standard harmonic filter*

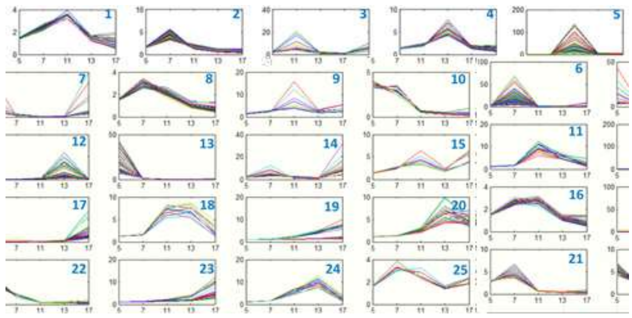

Fig. 3 *Network clusters. X-axis: harmonic order and Y-axis: HDGF*

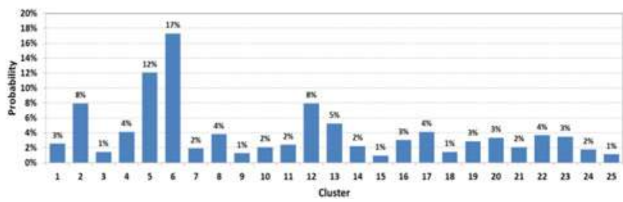

Fig. 4 *Probability that a network scenario falls into a specific cluster group*

The probability of a network scenario belonging to one of the cluster groups is shown in Fig. 4. Cluster 6 where network conditions show a resonance frequency at the seventh harmonic order is the most probable cluster (with 17%) whereas other clusters such as Cluster 15 contains only 1% of network scenarios.

6.3 Step III – filter optioneering

The purpose of filter optioneering is to identify types and parameters of the filters that can be considered as candidates for a standard harmonic filter.

An exhaustive range of filter scenarios including the C-type, single tuned and double tuned filters were created. In total 3100 filter scenarios were considered. As previously mentioned,

Table 4 Filter scenarios which bring the HDGFs of all representative network conditions within the permissible HDGFs

	Filter connected at sub B – 132 kV				Filter connected at PCC-1 33 kV			
Option	Units	Mvar	Tuned H	R_p	Units	Mvar	Tuned H	R_p
1	2	7.5	5th	600	—	—	—	—
2	2	10	5th	600	—	—	—	—
3	2	15	3rd	200	—	—	—	—
4	2	15	5th	200	—	—	—	—
5	1	7.5	7th	600	2	7.5	5th	200
6	1	10	7th	600	1	7.5	5th	200
7	1	15	5th	200	1	7.5	3rd	200

Units are the number of harmonic filters, tuned H is the harmonic order at which filter is tuned, and R_p is the parallel damping resistance of the C-type filter.

Sub-132 kV and PCC-1 33 kV nodes of the network are candidate locations for filter connection.

The filter scenarios were tested on representative network conditions identified in STEP II. The HDGFs of representative networks were re-calculated when each filter scenario is applied. Those filter scenarios, which bring the HDGFs of all representative network conditions within the permissible ranges were considered as possible candidate for a standard harmonic filter.

Insertion of a harmonic filter changes the network's frequency impedance characteristic for a wider frequency range. Hence, while the HDGFs may be improved at some harmonic orders, other HDGFs may be increased. This significantly reduces the number of filter options, which can satisfy the harmonic compliance requirements.

Filter scenarios connected at only the 33 kV busbar (PoC-1) did not satisfy the HDGFs criteria. Instead, some filter scenarios connected only at the 132 kV busbar and some combined connections both at 33 and 132 kV were identified as possible options for a standard harmonic filter. In addition, only the C-type filter appeared to be a possible common solution among all the representative networks. Single tuned and double tuned filters did not satisfy the HDGFs criteria. Table 4 shows the seven filter options, which can satisfy the HDGF criteria for representative network conditions.

6.4 Step IV – filter selection

The purpose of filter selection is to identify a filter design, which can maintain the HDGFs within the permissible levels for the majority of networks conditions. In Section 6.3, a list of filter options, which were suitable for representative network conditions were identified. The list included seven filter designs, which are tuned at different frequencies and connected either at 132 kV node or at 33 and 132 kV nodes.

For the filter selection process, all the network scenarios, which included a single wind farm connection were considered. The impact of each filter option on the HDGFs of the network scenarios was calculated and checked whether they were within the permissible limits. It was expected that filter options may not work for the entire network scenarios and there would be some scenarios where HDGFs were still outside the permissible levels. In order to compare the effectiveness of filter options, a probability of success for each filter option was calculated to show what percentage of the network scenarios can be covered. Among all the filter options in Fig. 5, option 1 and option 2 showed low success probabilities especially in complying with HDGF requirements for 15th, 21st, and 23rd harmonic orders.

It was observed that filter options 5, 6, and 7 can satisfy the HDGFs criteria for almost 95% of network conditions. These three successful harmonic filter options (5, 6, and 7) include the connections of harmonic filters at both 33 and 132 kV nodes when one wind farm is connected. For the second and third wind farm connections, however, we assume only the 33 kV harmonic filter of a filter option will be added to the network. This is to avoid excessive reactive power injection at 132 kV network which may result in over voltage issues at different parts of network. In addition, additional 132 kV harmonic filters can significantly increase the overall cost of the scheme, which may not be necessary.

After adding second and third wind farm in stages, the results consistently showed that filter option 7 can satisfy the harmonic performance criteria in the majority of network conditions for up to three wind farm connections. On this basis, it is proposed that filter option 7 can be considered as the standard harmonic filter. The variations of HDGFs within the permissible level envelope for odd harmonic orders when using filter option 7 are shown in Fig. 6 providing a visual aid in understanding the performance of these filters.

In summary, the C-type passive harmonic filters which should be connected at each stage while the number of wind farms increases are shown in Fig. 7.

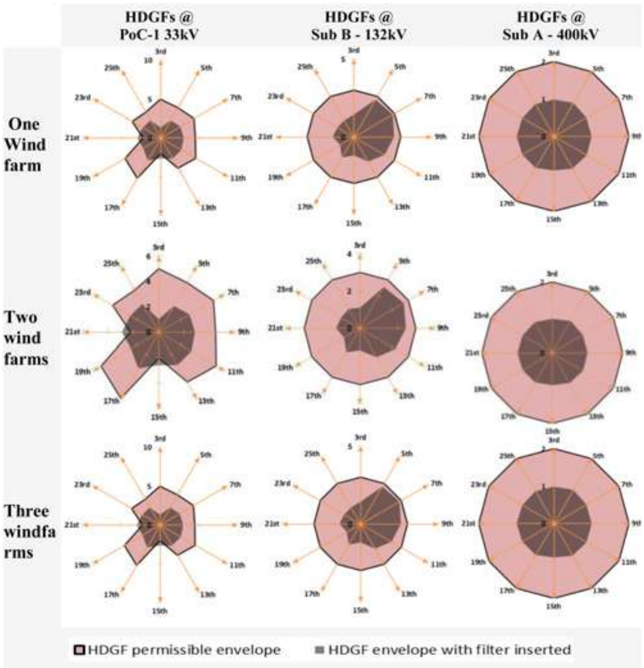

Fig. 5 *Component values of the standard harmonic filter scheme*

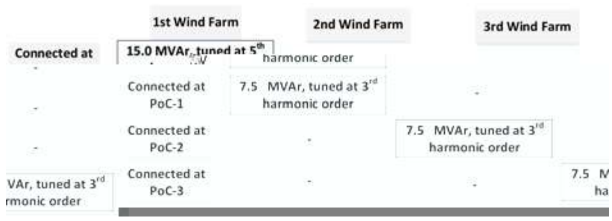

Fig. 6 *HDGFs envelopes with filter option 7 inserted*

	C1 [uF]	C2 [uF]	L [mH]	Rs [ohm]	Rp [ohm]
132kV 15.0 Mvar C-type Passive Filter tuned at 5th HO	63.05	2.74	160.69	0.10	200
132kV 15.0 Mvar C-type Passive Filter tuned at 3rd HO	167.56	21.92	60.47	0.04	200

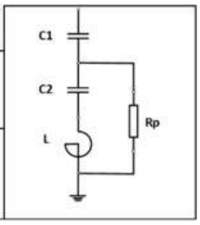

Fig. 7 *Sequence of C-type harmonic filter connections under the standard harmonic filter scheme*

The values of the harmonic filter components for option 7 is determined as those given in Fig. 5.

7 Conclusions and on-going works

In this paper a standard passive harmonic scheme can be used for majority of wind farm connections were proposed. The proposed solution includes connections of C-type harmonic filters at the 33 and 132 kV voltage levels. This study demonstrated that a standardised harmonic filter scheme could be considered at a very early stage when a connection offer is made to a wind farm developer. In this way, all the costs and risks associated with power quality requirements can be considered and evaluated at early stage of wind farm construction.

We are now developing the technical specifications of the proposed standard harmonic filter, which include the footprints, detailed component ratings of the harmonic filters, insulation coordination requirements, and also specifications for the circuit breakers of the harmonic filters. This will inform procurement and manufacturing of the proposed standard harmonic filter.

8 References

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