AC HARMONIC FILTER DESIGN METHODOLOGY FOR HVDC SYSTEMS

WC Stemmet, J Smith & G Atkinson-Hope

Cape Peninsula University of Technology, Electrical Engineering Department, P.O. Box 652, Cape Town, 8000

Abstract. The HVDC CIGRE benchmark network and published literature thereon discloses the use of harmonic filters and parameter values are given for the components. The methodologies on how to design the filters used is not disclosed. The focus of this paper is to identify the types of AC harmonic filters applied and to develop design methodologies for the CIGRE filter used. At both the converter stations, a combination of a 2nd order high-pass damped filter and a CIGRE C-type filter is identified. Methodologies were developed for these filters. The developed methodologies were compared and evaluated to ascertain discrepancies in filter components and results that arose due to the CIGRE using a non generalised C-type filter. The methodologies were adapted to accommodate these changes, and the results then became the same. The filter performances were evaluated in terms of the individual and total harmonic distortion indices and frequency sweeps. The filter design methodology was shown to be effective and can serve as a benchmark.

Key Words: 2nd Order high- pass damped harmonic filters, C-Type filters, CIGRE HVDC Benchmark

1 INTRODUCTION

The CIGRE Benchmark was the first attempt to create a reference network for HVDC simulation studies. The benefit of a reference network is that it allows for the comparison of different simulation methods, mostly control systems [3] and [4].

In 2006, a detailed modelling of the CIGRE benchmark using PSCAD software was published [9]. Little emphasis was placed on the design methodology of the harmonic filters at both ends of the converter stations. The CIGRE network does not include harmonic filters on its DC transmission network, only on the rectifier and inverter AC sides.

The types of filters used and their parameters are given for the CIGRE network. The shortcoming in literature is that the design methodology for the filter types is not described. There is thus a need to develop a design methodology for these filter types and test this methodology by applying it to the CIGRE system. Also to demonstrate that the developed methodology leads to the parameter values that agree with 2nd order high-pass damped filter and a C-type filter used in the benchmark.

2 RESEARCH STATEMENT

The emphasis of this paper is to develop a design methodology for the 2nd order high-pass damped and C-type filters for both the converter stations of the CIGRE HVDC benchmark, apply the methodology and compare the filter parameters to that of the published filter data. The effectiveness of the filters will also be demonstrated through analysis of the results when the design is applied and simulation studies are conducted.

3 CIGRE HVDC BENCHMARK

The benchmark is a 12-pulse monopolar system with the following operating parameters: 500 kV, 1000 MW and 2 kA. The rectifier is connected to a 345 kV, 50 Hz, AC system and the inverter is connected to a 230 kV AC system [3].

HVDC systems transfer bulk power using large nonlinear equipment (converter valves) causing harmonic penetration into its associated AC networks. Harmonic mitigation equipment has to be installed. With 12-pulse converters two techniques are used for mitigation, transformer configurations and harmonic filters. These techniques prevent harmonics from entering the rest of the power system [1] and [8]. Line commutated HVDC systems draw large amount of reactive power and therefore must have capacitive reactive compensation to supply the converters. To save costs this capacitor bank forms part of the harmonic filter design, thus reactive power compensation is provided by a combination of capacitor banks and harmonic filters [4].

The focus for the research is to design high-pass damped harmonic filters for HVDC systems. In Figure 1, the typical configuration of these harmonic filters is illustrated:

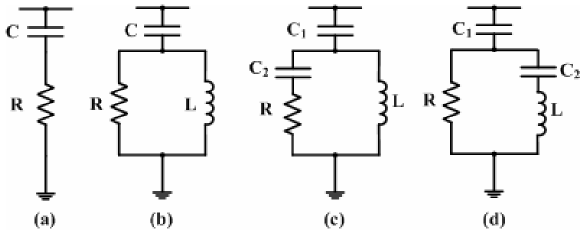

Fig.1: High-pass damped filters: (a) First order; (b) second order; (c) third order; (d) C-type

The CIGRE benchmark uses the 2nd order high-pass damped filter (Figure 1b) and the C-type filter (Figure 1d) at both the rectifier and inverter ends.

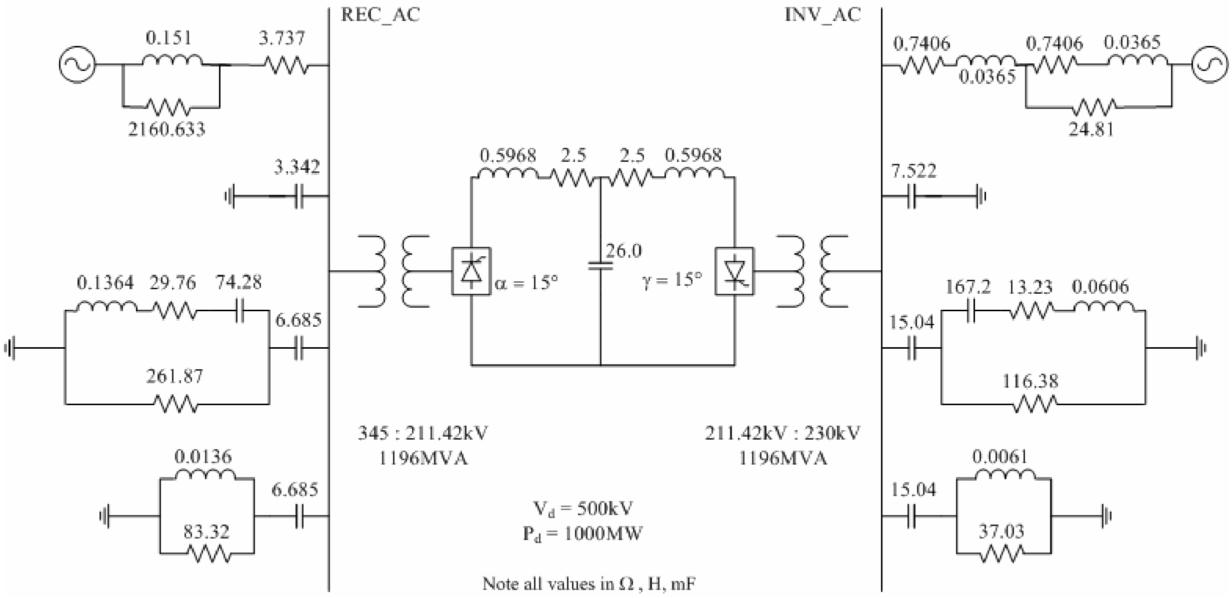

Fig. 2: CIGRE HVDC Benchmark

4 MITIGATION SOLUTIONS

4.1 Transformer vector groups

The 12-pulse monopolar configuration for the benchmark is obtained by connecting two 6-pulse rectifiers in series. Six-pulse converters generate characteristic harmonic currents of the order:

$$h = np \pm 1 \tag{1}$$

Where n is any positive integer and p is the pulse number. The first mitigation technique is the use of transformer configurations to prevent the 5th and 7th harmonics penetrating into the AC system (primary side).

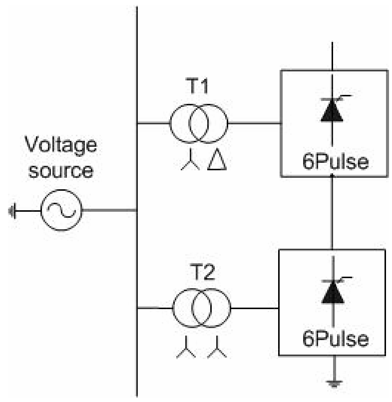

Fig.3: Commutating transformer vector groups

The total AC current flowing into the AC network has the following Fourier components shown in (2):

$$i_T = C_1 \cos\left(\omega t + \frac{\pi}{6}\right) + C_{11} \cos\left(11\omega t - \frac{\pi}{6}\right) + C_{13} \cos\left(13\omega t + \frac{\pi}{6}\right) + \ldots \tag{2}$$

The AC current waveform contains characteristic 12-pulse harmonic currents (11th, 13th and higher) and the lower order 6-pulse harmonics (5th and 7th) are eliminated in the arrangement shown in Figure 3:

4.2 Reactive power compensation

The reactive power compensation for the converter is supplied by the capacitor bank and the two filters.

The rating of a harmonic filter is defined by the amount of reactive power the filter supplies at fundamental frequency. The direction of reactive power flow in a HVDC system can be seen in Figure 4.

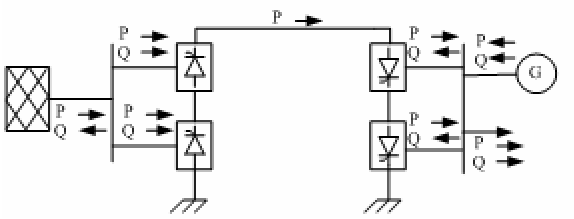

Fig. 4 HVDC Transmission Network Power Flow Diagram

The power factor for a converter station is calculated by (3):

$$\cos(\phi) = \frac{\cos(\alpha) + \cos(\alpha + \mu)}{2} \approx 0.866 \tag{3}$$

For the benchmark the firing angle (α) is 15° and the overlap angle (μ) is 25°, thus the approximate power factor is 0.866 lagging. The amount of reactive power required for the converter station is often expressed as a percentage of the DC power to be transmitted and is given by (4) [8]:

$$\tan(\phi) = \frac{Q_1}{P_1} = 0.577 \approx 0.6 \tag{4}$$

For CIGRE, a 1000MW is to be transferred from the rectifier side to the inverter side. Thus 600Mvar has to be supplied from the capacitor bank and the two harmonic filters connected to a converter station.

5 METHODOLOGY

The ideal objective for filter design is to nullify all waveform distortion; however, the ideal criterion is impractical for technical and economical reasons. A more practical approach is to reduce the distortion problem to an acceptable level.

In a real world, characteristic harmonics occur in systems but when they are asymmetrical and unbalanced the converters also generate third harmonic currents. They pass through transformer configurations as they act like positive sequence and are not blocked. In order to eliminate characteristic and low order harmonic currents, HVDC systems typically use C-type and 2nd order damped filters to eliminate all these harmonics.

These types of filters (Figures 1 and 2) contain capacitors and the determination of amount of reactive power that they must supply needs initially to be fixed. From the CIGRE benchmark and (4) the converters requires approximately 600 Mvar. Allowing for tolerances the value of 625 Mvar is selected. The ratio for the contribution and from a cost point of view, the filters and the reactive compensation is as follows:

- 40 % from second order high pass filter
- 40 % from C-type high pass filter
- 20 % from compensation capacitor bank

Thus the two harmonic filters connected to the rectifier station contribute 500 Mvar (80 %), and assuming that the capacitance is equally divided between them, each filter should contribute 250 Mvar (40 %). The reactive power compensation bank contributes the remaining 20 % (125 Mvar). Similar approach is followed on the inverter side.

Three methodologies are needed to be developed for the design of the filters for CIGRE benchmark:

- 2nd order high-pass damped filter
- General C-type damped filter
- CIGRE C-type damped filter

5.1 Second order high- pass damped filter

- **Step1:** Filter design criteria for lowest characteristic harmonic order. The filter at the rectifier station is designed with the following parameters: voltage rating (V_1) of 345 kV, reactive power (Q_1) of 250 Mvar, angular velocity (ω) of 314.159 rad/s, resonant harmonic order (h_r) for the 11th H/O and a quality factor (q): 2.5, typically ($0.5 < q < 5$).

In Figure 5, are the configuration and the impedance characteristic for the filter:

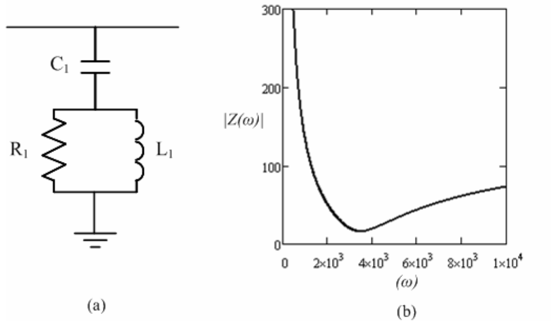

Fig. 5: 2nd order high-pass damped filter: (a) configuration; (b) impedance characteristic

- **Step 2:** Obtain filter component values. The filter components are determined with the use of the following (5) to (10), [6], The capacitive reactance is:

$$X_C = \frac{V_1^2}{Q_1} \tag{5}$$

The value for the capacitor (C_1) is:

$$C_1 = \frac{1}{\omega \cdot X_C} \tag{6}$$

The inductive reactance is:

$$X_L = \frac{X_C}{h_r^2} \tag{7}$$

The value for inductor is:

$$L_1 = \frac{X_L}{\omega} \tag{8}$$

The characteristic reactance is:

$$X_N = \sqrt{X_L \times X_C} = \sqrt{\frac{L_1}{C_1}} \tag{9}$$

The value for the resistor is:

$$R_1 = X_N \times q \tag{10}$$

Step3: Compare harmonic filter parameters based on Step 1 to CIGRE published filter values.

Harmonic filters are usually tuned slightly lower than the harmonic component to be filtered to provide a margin of safety in case there is some change in system parameters that would alter the resonant frequency. If they were tuned exactly to the resonant frequency of the system, changes in either capacitance or inductance with temperature or failure might shift the resonance from the harmonic component being filtered [8].

Step 4: Redesign the filter to accommodate potential changes in system parameters.

Step 5: Evaluate the performance of the filter.

A similar methodology is followed to design the 2nd order high- pass damped filter at the inverter station, but at a different voltage level.

5.2 General C-type damped filter

Figure 6, shows the configuration and the impedance characteristic for a general filter of this type:

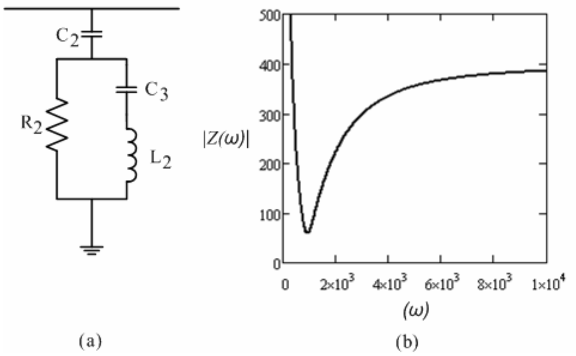

Fig. 6: C-type damped filter: (a) configuration; (b) impedance characteristic

It is necessary to first review the general design methodology.

- **Step 1:** Filter design criteria for lowest characteristic harmonic order including the intermediate factor (m). The filter at the rectifier station is designed with the following parameters: voltage rating (V_1) of 345 kV, reactive power (Q_1) of 250 Mvar, angular velocity (ω) of 314.159 rad/s, resonant harmonic order (h_r) for the 3rd harmonic order, a quality factor (q) of 2.5, typically ($0.5 < q < 5$) and an intermediate factor (m) of ∞.

- **Step 2:** Obtain filter component values for the filter. The filter. The filter components are determined with the use of the (11) to (15), [5]: The capacitive reactance is:

$$X_C = \frac{V_1^2}{Q_1} \tag{11}$$

The value for the capacitor (C_2) is:

$$C_2 = \frac{1}{\omega \cdot X_C} \tag{12}$$

The value for the capacitor (C_3) is:

$$C_3 = \frac{h_r^2 - 1}{m^2 - m\sqrt{m^2 - 1}} \times \frac{Q_1}{2 \cdot V_1^2 \cdot \omega} \tag{13}$$

The value for the inductor (L_2) is:

$$L_2 = \frac{m^2 - m\sqrt{m^2 - 1}}{h_r^2 - 1} \times \frac{2 \cdot V_1^2 \cdot \omega}{Q_1} \tag{14}$$

The value for the resistor (R_2) is:

$$R_2 = \frac{q \cdot V_1^2}{h_r \cdot Q_1} \tag{15}$$

- **Step 3:** Obtain the equivalent series tuned filter with the intermediate factor (m), ($m \geq 1$). According to (17), these final parameters are based on the assumption that the factor (m), is infinite.

$$g(m) = m^2 - m\sqrt{m^2 - 1} \tag{16}$$

If $m \to \infty$, then (15) resolves to:

$$\lim_{m \to \infty} g(m) = \lim_{m \to \infty} (m^2 - m\sqrt{m^2 - 1} = 0.5 \tag{17}$$

This means there are no resistance (R_2), in parallel, thus the C-type filter become a single tuned filter as shown in Figure 7.

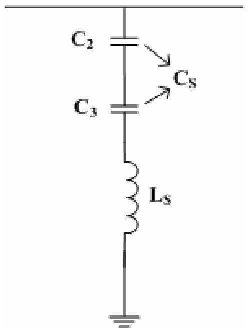

Fig. 7: Equivalent single tuned filter

From the single-tuned filter (Figure 7) the following components can be calculated: The parameters (C_3) and (L_S) for the filter can be obtained using (18) to (21).

$$C_S = \frac{(h_r^2 - 1) \cdot Q_1}{\omega \cdot V_1^2} \tag{18}$$

The inductor (L_S) is calculated by:

$$L_S = \frac{V_1^2}{(h_r^2 - 1) \cdot \omega \cdot Q_1} \tag{19}$$

From (20) and (21) the filter components of the general C-type filter can be obtained;

$$C_S = \left(\frac{1}{C_2} + \frac{1}{C_3} \right)^{-1} = \frac{(h_r^2 - 1) \cdot Q_1}{h_r^2 \cdot \omega \cdot V_1^2} \tag{20}$$

The value for the inductor (L_2) is:

$$L_S = L_2 \tag{21}$$

A similar process was followed to design the general C-type damped filter at the inverter station, but at a different voltage level.

5.3 CIGRE C-type damped filter

The CIGRE benchmark does not use the general C-type damped harmonic filter. It uses the type shown Figure 8b.

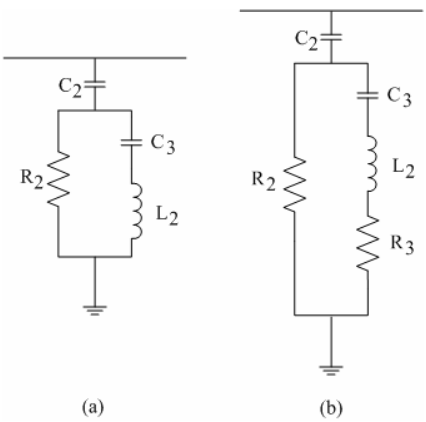

Fig. 8: C-type damped filters: (a) Section 4; (b) Default CIGRE benchmark

The CIGRE has an additional resistance (R_3) in the series tuned arm of the filter and its value needs to be determined. This is obtained using:

The characteristic reactance is:

$$X_N = \sqrt{\frac{L_2}{C_3}} \tag{22}$$

Resistor (R_3) is:

$$R_3 = \frac{X_N}{q_S} \tag{23}$$

6 HARMONIC FILTER EVALUATION

The methodologies are now applied.

The 2nd order high-pass damped harmonic filter components are compared to that of the filter components provided with the CIGRE benchmark (Section 5.1, Step 3) is shown in Table 1.

The respective design methodologies for the filters are applied, and to check the effectiveness the following equation is used:

$$|\%Change| = \frac{CIGRE - Design}{CIGRE} \times 100\% \tag{24}$$

TABLE 1: Comparison of the 2nd order high-pass harmonic filter components

Rectifier			
2nd Order HP Filter			
Component	**Designed**	**CIGRE**	**|% Change|**
C_1 (μF)	6.686	6.685	0.015
L_1 (H)	0.0125	0.0136	8.088
R_1 (Ω)	108.205	83.32	29.867
Inverter			
2nd Order HP Filter			
Component	**Designed**	**CIGRE**	**|% Change|**
C_1 (μF)	15.04	15.04	0
L_1 (H)	0.0056	0.0061	8.196
R_1 (Ω)	48.091	37.03	29.870

TABLE 2: Comparison of C-type damped harmonic filters components

Rectifier			
C-type damped filter			
Component	**Designed**	**CIGRE**	**|% Change|**
C_2 (μF)	6.686	6.685	0.015
C_3 (μF)	53.49	74.28	27.989
L_2 (H)	0.1894	0.1364	38.856
R_2 (Ω)	396.75	261.87	51.506
R_3 (Ω)	---	29.76	---
Inverter			
C-type damped filter			
Component	**Designed**	**CIGRE**	**|% Change|**
C_2 (μF)	15.04	15.04	0
C_3 (μF)	120.3	167.2	28.050
L_2 (H)	0.0842	0.0608	38.487
R_2 (Ω)	176.33	116.38	51.512
R_3 (Ω)	---	13.23	---

From Tables 1 and 2, it can be seen that the designed parameters differ from the CIGRE values, thus adapted filters need designing. To adapt the 2nd order high-pass damped harmonic filter it is required to change the design criteria. This is achieved by reducing the resonant harmonic order (h_r) from 11 to 10.55 and the quality factor (q) from 2.5 to 1.85.

TABLE 3: Comparison of the 2nd order high-pass harmonic filter components

Rectifier			
2nd Order HP Filter			
Component	**Re_designed**	**CIGRE**	**|% Change|**
C_1 (μF)	6.685	6.685	0
L_1 (H)	0.0136	0.0136	0
R_1 (Ω)	83.487	83.32	0.2
Inverter			
2nd Order HP Filter			
Component	**Re_designed**	**CIGRE**	**|%Change|**
C_1 (μF)	15.04	15.04	0
L_1 (H)	0.0061	0.0061	0
R_1 (Ω)	37.11	37.03	0.2

With the C-type damped filter, Figure 8 (b), an additional resistor (R_3) has to be added to the filter. In order to obtain similar results to that of the CIGRE benchmark model, the resonant harmonic order (h_r) was increased from 3 to 3.5 and the quality factor (q) was decreased from 2.5 to 2. For R_3, a quality factor of 1.5 was used. The results are displayed in Table 4.

TABLE 4: Comparison of C-type damped harmonic filter components at both the rectifier and inverter station

Rectifier			
C-type damped filter			
Component	**Designed**	**CIGRE**	**|% Change|**
C_2 (μF)	6.685	6.685	0
C_3 (μF)	75.22	74.28	1.27
L_2 (H)	0.1347	0.1364	1.25
R_2 (Ω)	272.06	261.87	3.89
R_3 (Ω)	28.21	29.76	5.21
Inverter			
C-type damped filter			
Component	**Designed**	**CIGRE**	**|% Change|**
C_2 (μF)	15.04	15.04	0
C_3 (μF)	169.23	167.2	1.21
L_2 (H)	0.0601	0.0608	1.31
R_2 (Ω)	120.91	116.38	3.89
R_3 (Ω)	12.54	13.23	5.21

For the quality factor (q_S) of 1.5 the error for R_3 is approximately 5%. If the q-factor is adjusted, more accurately, then error will disappear.

7 HARMONIC FILTER PERFORMANCE

Now that the filter parameters have been established, the performance of the filters together with the reactive compensation and the AC network needs to be checked for effectiveness.

The characteristic harmonic currents generated by the each of the 6-pulse converters at the rectifier side (commuting transformer secondary) are shown in Figure 9 and 10.

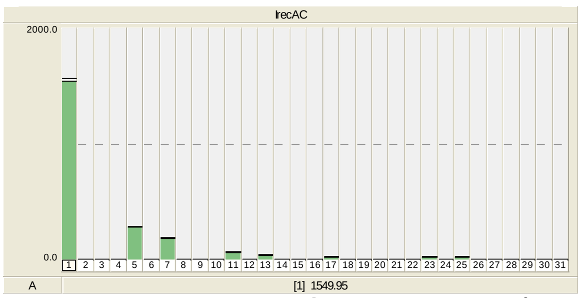

Fig. 9: Harmonic currents at the commutating transformer secondary (Delta/Wye)

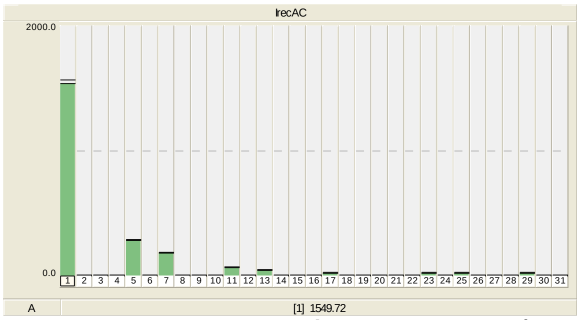

Fig. 10: Harmonic currents at the commutating transformer secondary (Wye/Wye)

To demonstrate that the AC current waveform contains characteristic 12-pulse harmonic currents (11th, 13th and higher) and the lower order 6-pulse harmonics (5th and 7th) are eliminated at REC_AC is shown in Figure 11:

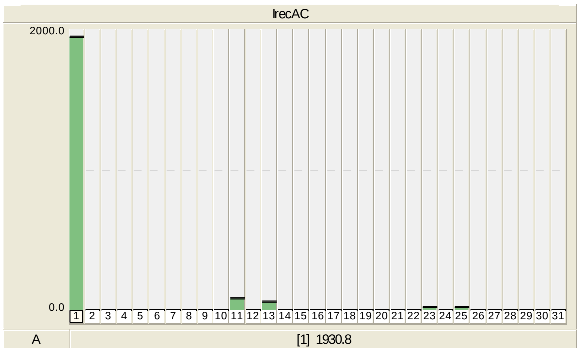

Fig. 11: Harmonic currents at REC_AC

The same characteristic 12- pulse harmonic currents (11th, 13th and higher) were present at INV_AC at the inverter side.

To evaluate the combined performance of the 2nd order high-pass damped filter and the C-type filter at the rectifier and inverter sides of the HVDC system, the following voltage and current indices were used (25) and (26):

Individual Harmonic Distortion (HD) is:

$$HD_M = \frac{M_h}{M_1} \times 100\% \tag{25}$$

The Total Harmonic Distortion (THD) is:

$$THD_M = \frac{\sqrt{\sum_{h=2}^{31} M_h^2}}{M_1} \times 100\% \tag{26}$$

The harmonic voltage index results at REC_AC and INV_AC are shown in Tables 5 and 6.

TABLE 5: Harmonic voltage index results at REC_AC

REC_AC			
Harmonic Voltage Index Results			
Index	**Design**	**Adapted**	**CIGRE**
HD_5 (%)	0.018	0.018	0.017
HD_7 (%)	0.002	0.006	0.001
HD_{11} (%)	0.622	0.777	0.778
HD_{13} (%)	0.551	0.620	0.617
HD_{17} (%)	0.003	0.001	0.002
HD_{19} (%)	0.001	0.002	0.001
HD_{23} (%)	0.432	0.347	0.348
HD_{25} (%)	0.367	0.303	0.297
THD (%)	1.008	1.101	1.103

TABLE 6: Harmonic voltage index results at INV_AC

INV_AC			
Harmonic Voltage Index Results			
Index	**Design**	**Adapted**	**CIGRE**
HD_5 (%)	0.012	0.031	0.074
HD_7 (%)	0.005	0.025	0.005
HD_{11} (%)	0.484	0.606	0.619
HD_{13} (%)	0.380	0.462	0.447
HD_{17} (%)	0.004	0.006	0.004
HD_{19} (%)	0.002	0.006	0.002
HD_{23} (%)	0.440	0.339	0.355
HD_{25} (%)	0.349	0.277	0.270
THD (%)	0.836	0.915	0.894

The harmonic current index results at REC_AC and INV_AC are shown in Tables 7 and 8.

TABLE 7: Harmonic current index results at REC_AC

REC_AC			
Harmonic Current Index Results			
Index	**Design**	**Adapted**	**CIGRE**
HD_5 (%)	0.022	0.040	0.026
HD_7 (%)	0.003	0.023	0.004
HD_{11} (%)	4.444	4.376	4.392
HD_{13} (%)	2.906	2.843	2.850
HD_{17} (%)	0.007	0.008	0.008
HD_{19} (%)	0.004	0.011	0.002
HD_{23} (%)	0.966	0.957	0.975
HD_{25} (%)	0.863	0.868	0.853
THD (%)	5.467	5.378	5.397

TABLE 8: Harmonic current index results at INV_AC

INV_AC			
Harmonic Current Index Results			
Index	**Design**	**Adapted**	**CIGRE**
HD_5 (%)	0.005	0.018	0.042
HD_7 (%)	0.021	0.021	0.036
HD_{11} (%)	3.393	3.365	3.447
HD_{13} (%)	2.023	2.039	2.047
HD_{17} (%)	0.006	0.005	0.010
HD_{19} (%)	0.005	0.006	0.009
HD_{23} (%)	0.951	0.930	0.958
HD_{25} (%)	0.793	0.795	0.756
THD (%)	4.145	4.131	4.203

Small differences were found in the results obtained for the individual voltage and current harmonic distortion results, and similar results were obtained for the total voltage and current harmonic current distortion index results obtained at both REC_AC and INV_AC. The low percentage values demonstrate that the combined performance of the filters is effective proving that the developed design methodology for the filters is correct.

To show the frequency response of the integrated HVAC/HVDC system that includes the AC source impedance, harmonic filters and reactive compensation, a frequency sweep study was conducted at both REC_AC and INV_AC buses in the network.

The role of the AC source impedance on both the rectifier and inverter sides influences the performance of the harmonic filters used. Due to the nature of these impedances (R-R-L and R-L-L, configuration types, Figure 2, respectively) the resonant frequency point and the damping are effected. The R-L-L type reveals a higher damping at the lower harmonic orders, thus sweeps are conducted to evaluate responses.

In Figure 12 and 13, the frequency responses at REC_AC are displayed.

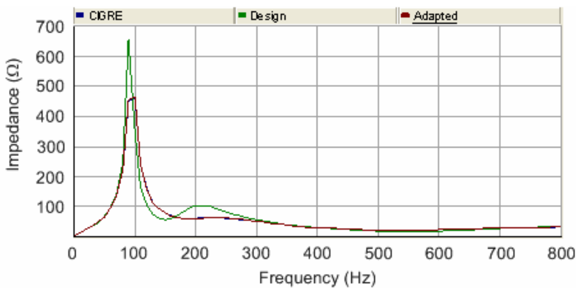

Fig. 12: Impedance magnitude obtained at REC_AC

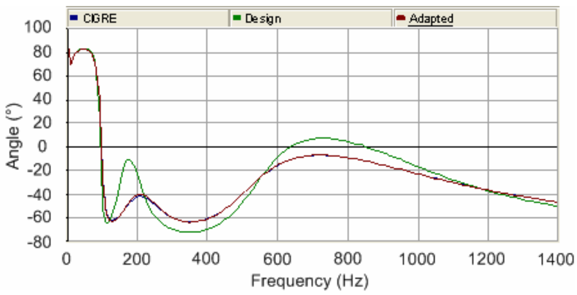

Fig. 13: Impedance angle obtained at REC_AC

From literature [3], a second harmonic resonance at the AC side should be present, due to the weak inverter side. From Figure 12, a harmonic resonance close to the 2nd harmonic order (94 Hz) can be seen for the designed harmonic filters as well as the adapted harmonic filters compared to the CIGRE harmonic filters, proving the work conducted.

The process was repeated and in Figure 14 and 15, the frequency responses at INV_AC are displayed.

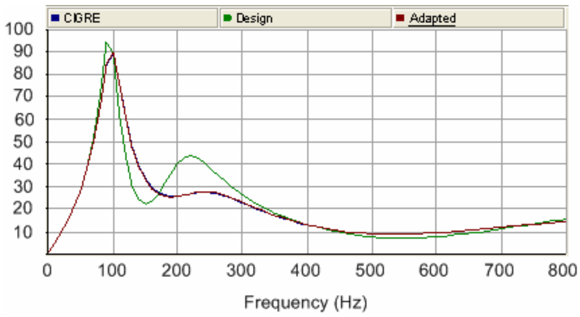

Fig. 14: Impedance magnitude obtained at INV_AC

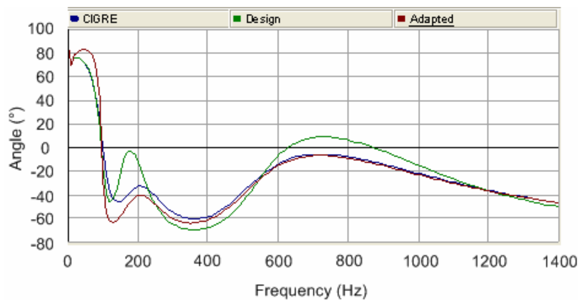

Fig. 15: Impedance angle obtained at INV_AC

With the dominant R-L-L AC system configuration present at the at the inverter side, the higher damping for lower harmonic orders can be seen in Figure 14, where the impedance magnitude at the resonant frequency is below 100 Ω, compared to the impedance (near 500 Ω) at the rectifier side.

8 CONCLUSIONS

It was found necessary to identify the harmonic filter types used with the HVDC CIGRE benchmark network. They were identified as a 2nd order high-pass damped filter and a C-type damped filter at both the rectifier and inverter sides. On closer inspection it was found that the C-type used with the CIGRE network differed from the general C-type filter.

From this finding design methodologies for the 2nd order high-pass damped and CIGRE C-type filters for both the converter stations needed development. It was thus found necessary to develop three methodologies so that proper understanding of the design details is known.

The first methodology was for the 2nd order high-pass damped filter where choice of the resonant harmonic order (h_r) and the quality factor (q) are decisive in the design.

Before developing the CIGRE C-type methodology it was necessary to develop a methodology for a generalised C-type filter, especially as the design is more complex than the 2nd order high-pass filter. As with this filter it is necessary to include the intermediate factor (m) besides choosing the harmonic resonant order (h_r) and quality factor (q).

With HVDC systems typically there are two harmonic mitigation solutions, transformer vector groups and harmonic filters. These are reviewed and evaluated using the designed filters and the results demonstrated their effectiveness. The three methodologies were compared to ascertain discrepancies using a developed percentage change formula. Discrepancies were found and this was because general theory of filters is based on the elimination of the lowest characteristic harmonic order present. This is not true for the CIGRE benchmark, where filters are tuned to frequency other than a characteristic harmonic.

Filter performance was evaluated in terms of voltage and current individual and total harmonic distortion index results and frequency sweeps. The filters effectively reduced distortion, by shifting resonant frequency points and by providing suitable damping.

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BIOGRAPHIES

- **Willem Stemmet**
  E-mail: stemmetw@cput.ac.za
- **Johan Smith**
  E-mail: smithj@cput.ac.za
- **Prof. G. Atkinson-Hope**
  E-mail: atkinsonhopeg@cput.ac.za