ADAPTIVE TOOLS TO CONDUCT HARMONIC ANALYSIS USING TIME DOMAIN SOFTWARE

WC Stemmet, J Smith & G Atkinson-Hope

Cape Peninsula University of Technology (CPUT), South Africa, stemmetw@cput.ac.za

Keywords: Adaptive tools, harmonic analysis

Abstract

The non-linear behaviour of HVDC converters causes distorted voltage and current waveforms in the HVAC network to which it is connected [1]. Typically frequency domain software is used for conducting harmonic analysis (penetration and impedance scan studies) and results are displayed as steady-state quantities not taking into account the dynamic behaviour of the system components. A time domain software package is utilized to perform harmonic analysis and consider the dynamic behaviour of the system components. Thus the contribution of this work is the development of adaptive (compact) tools to simplify harmonic analysis procedures for investigating integrated HVAC/HVDC systems using time domain software. Results are generated and it is found that the developed tools are effective for conducting harmonic analysis using time domain software.

1 Introduction

Harmonics is a steady-state concept and integrated HVAC/HVDC networks are considered as time varying systems and therefore traditional harmonic analysis software tools are not adequate for taking into account the dynamic behaviour of the different elements in such networks [1]. Currently there is very little published on the utilization of time domain software to evaluate the impact of harmonics in power systems which include HVDC systems. There is thus a need to research how to conduct harmonic analysis in the time domain. The time domain software package that is used for this study is PSCAD/EMTDC. Tools are available in the library of this package for conducting studies but how to combine them so that established indices for analysis can be generated and simultaneously visualized is needed. To achieve these results harmonic analysis tools in the library were utilized and combined to develop adaptive tools to obtain established index results.

2 Research Statement

The objective of this project is to design and develop compact tools for the purpose of conducting harmonic analysis that includes both harmonic penetration and impedance scan studies to identify harmonic resonance conditions.

3 PSCAD Library Elements

In the master library of PSCAD/EMTDC version 4.2.1 the following elements are present to assist the user to conduct harmonic analysis [2].

3.1 Meters

To be able to conduct harmonic analysis, the voltages and currents in a network must be known [3]. The software comes equipped with devices to measure the voltage, current, real and reactive power.

3.1.1 Harmonic impedance component

To conduct harmonic resonance studies the software comes equipped with a harmonic impedance component, which allows the user to perform a frequency sweep at nodes in a system. Figure 1 shows the harmonic impedance (Zscan) component.

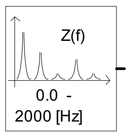

Figure 1: Harmonic impedance component

3.2 Continuous System Model Functions (CSMF)

3.2.1 Fast Fourier Transform Component (FFT component)

The FFT component and the output from a measuring device are used as a FFT tool to obtain the respective magnitudes and phase angles of the harmonic components of the time domain waveform. Figure 2 shows the FFT tool.

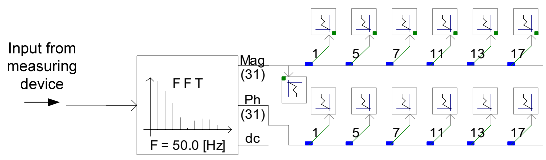

Figure 2: FFT tool

3.2.2 Harmonic Distortion Component

When conducting harmonic penetration studies the total harmonic distortion indices (V_{THD} and I_{THD}) and individual harmonic distortion indices (V_{HD} and I_{HD}) of an input signal needs to be measured.

Authorized licensed use limited to: Cape Peninsula University of Technology. Downloaded on May 10,2021 at 06:53:57 UTC from IEEE Xplore. Restrictions apply.

Figure 3 shows the FFT component and the harmonic distortion component which forms part of the Harmonic Distortion Calculator Tool.

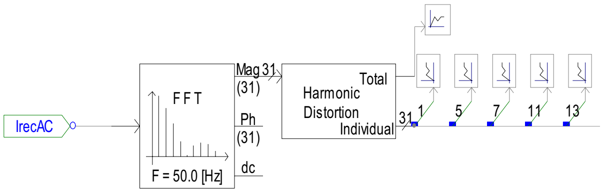

Figure 3: Harmonic distortion calculator tool

4 Adaptive Tools

4.1 Distortion Index Tool

Instead of conventional methods (calculating *RMS*, *HD* and *THD* index results, separately) being used to obtain the respective index results for voltages and currents it was found that a more complete single tool which can do all the index calculations simultaneously will save time and leave the workspace uncluttered. This tool can provide complex wave decomposition and provides the magnitudes as well as the phase angles of the various individual components. It can also calculate the individual as well as the total harmonic distortion indices and finally produce the *RMS* values for the input signal. This developed tool is shown in Figure 4 and is for a current input (similarly for a voltage input).

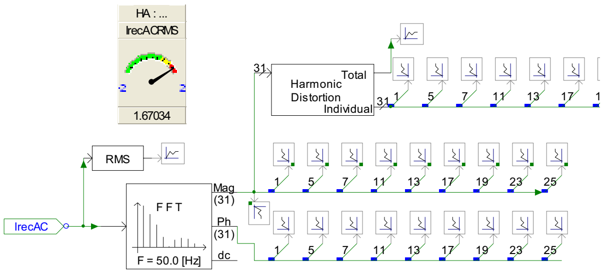

Figure 4: Distortion index tool

4.2 Harmonic Component Power Calculator Tool

A multimeter component can be used to measure real and reactive power. Total active power P_T (W) is calculated [4, 5]:

$$P_T = \sum_{h=1}^{\infty} P(h) \tag{1}$$

The total reactive power Q_T (var) is calculated using equation (2):

$$Q_T = \sum_{h=1}^{\infty} Q(h) \tag{2}$$

A shortcoming of a multimeter component is that it does not measure powers and phase angles per harmonic order nor does it give apparent power, displacement or true power factor quantities (*DPF* and *PF*). To obtain these outputs (except *PF*) it was necessary to develop a compact tool for this purpose, specifically the power components and power factors per harmonic order. The developed compact tool is shown in Figure 5. This is for fundamental frequency only. The same compact tool can be applied for all harmonic orders.

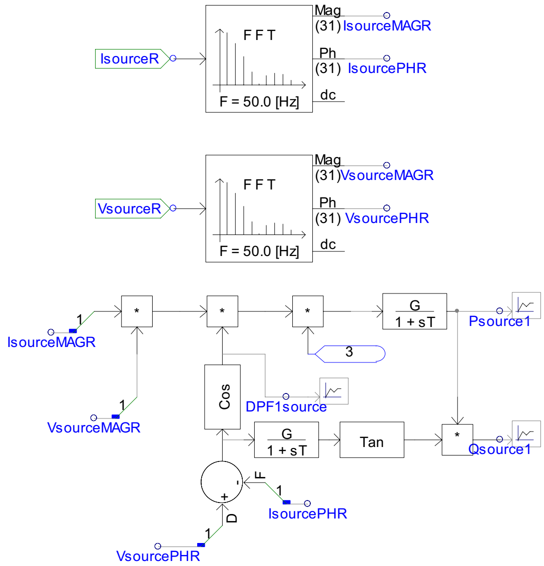

Figure 5: Compact harmonic component power calculator tool

4.3 Apparent Power and True Power Factor Tool

The multimeter component produces total real and reactive results but no total apparent power nor true power factor. To measure these outputs the following equations are used to develop another compact tool (Figure 6):

$$S_T = V_{rms} \cdot I_{rms} \tag{3}$$

$$PF = \frac{P_T}{S_T} \tag{4}$$

This tool uses STotalRec and TruePF for total apparent power and true power factor, respectively, namely:

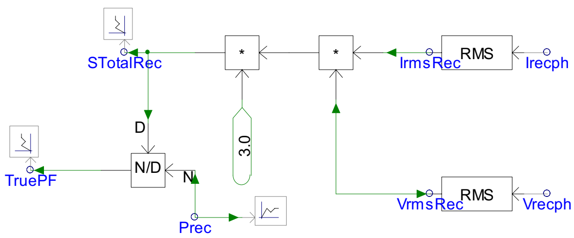

Figure 6: Apparent power and true power factor tool

Authorized licensed use limited to: Cape Peninsula University of Technology. Downloaded on May 10,2021 at 06:53:57 UTC from IEEE Xplore. Restrictions apply.

5 Case Study

The tools described in Section 4 are applied to the integrated HVAC/HVDC CIGRE Benchmark system [6, 7]. The case study is conducted with the harmonic filters and reactive compensation installed.

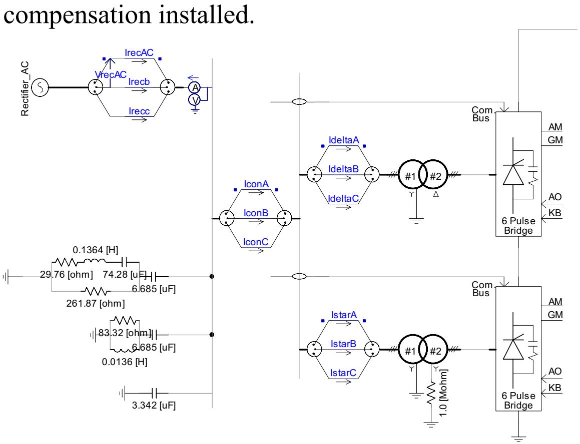

Figure 7: Case study diagram

Figure 7 shows the rectifier side. The 12-pulse configuration (two 6-pulse converters in series) uses a star-star and star-delta transformer configuration, harmonic filters and reactive compensation and the overall system is supplied from an AC source. The results of the harmonic analysis on the rectifier side are given.

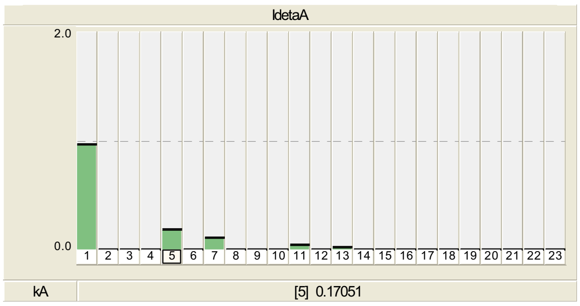

Figure 8: Harmonic analysis on the primary of the star-delta transformer

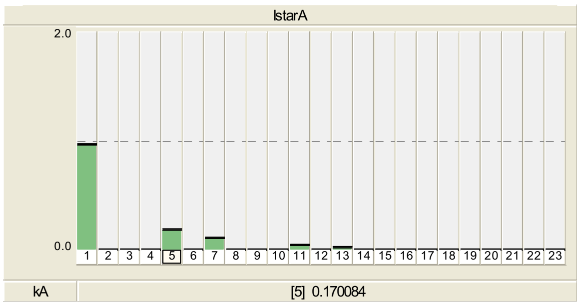

Figure 9: Harmonic analysis on the primary of the star-star transformer

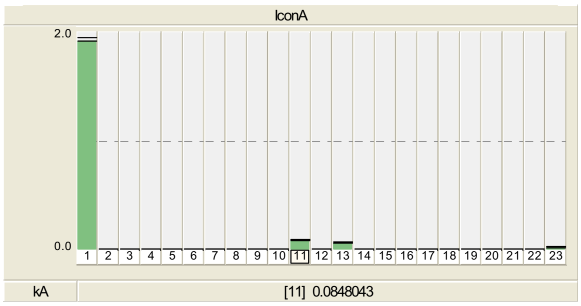

Figure 10: Harmonic analysis on the AC input side of the HVDC system.

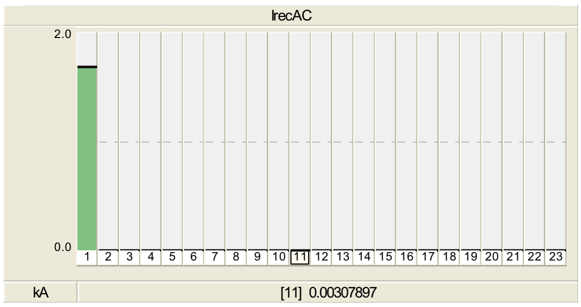

Figure 11: Harmonic analysis in the AC source path

From Figures 8 & 9 it can be seen that the converters each inject 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics. Figure 10 shows that the 5^{th} and 7^{th} harmonics are cancelled out by the combination of transformer configurations leaving 12^{th} and 13^{th} which is summed up. Figure 11 shows the analysis in the AC source path showing the importance of the harmonic filters which eliminates all the harmonics. To further demonstrate harmonic analysis, only the AC source path breakout point is reported on. Four different categories for the analysis are used, they are:

- Current harmonics (AC Fourier analysis including I_{HD}, I_{THD} and I_{RMS})
- Voltage harmonics (AC Fourier analysis including V_{HD}, V_{THD} and V_{RMS})
- Power components (individual and total powers).
- Impedance scans (AC busbar).

5.1 Current Harmonics

The current harmonics are measured. The harmonic magnitudes and phase angles are noted and the individual and total harmonic distortion is calculated using the tools and checking by hand. Only one phase is examined. The output from the ammeter (IrecAC, Figure 7) is used as an input to the "Distortion Index Tool" (Figure 4) which provides all the different indices required. The "FFT Tool" that is present in the developed tool provides the magnitudes and phase angles of the fundamental frequency and its harmonics.

Authorized licensed use limited to: Cape Peninsula University of Technology. Downloaded on May 10,2021 at 06:53:57 UTC from IEEE Xplore. Restrictions apply.

The harmonics are negligible and only the fundamental has a significant value due to harmonic filtering. The "Distortion Index Tool" (Figure 4) is used to obtain the total and individual harmonic distortion indices. To prove the effectiveness of the developed tool these different indices are checked using a MathCAD supported hand calculation method.

Rectifier Side	PSCAD	Hand calculation
I_{HD11}	0.18433%	0.1843%
I_{HD13}	0.12485%	0.1248%
I_{HD23}	0.04300%	0.0430%
I_{HD25}	0.03439%	0.0344%
I_{THD}	0.26255%	0.2293%
I_{RMS}	1.6703 kA	1.6703 kA
Inverter Side	PSCAD	Hand calculation
I_{HD11}	0.23089%	0.2342%
I_{HD13}	0.18087%	0.1809%
I_{HD23}	0.05341%	0.0534%
I_{HD25}	0.04244%	0.0425%
I_{THD}	0.43876%	0.3037%
I_{RMS}	2.4298 kA	2.4295 kA

Table 1: Rectifier and inverter current distortion results

The individual current distortion and I_{RMS} is identical for both the hand calculation and the PSCAD results. Small discrepancies exist for the total current harmonic distortion due to the fact that the hand calculation only considered the characteristics harmonics whereas PSCAD includes the non-characteristic harmonics (small quantities).

5.2 Voltage Harmonics

The same approach to that of the current harmonics is followed. The harmonic magnitudes and phase angles are examined and the individual, total voltage harmonic distortion and RMS voltage are calculated. The results obtained from the developed tool (Figure 4) when applied to voltage harmonics on the rectifier side as well as the results from hand calculations are shown in Table 2.

Rectifier Side	PSCAD	Hand calculation
v_{HD11}	0.773926%	0.7739%
v_{HD13}	0.615185%	0.6152%
v_{HD23}	0.34933%	0.3493%
v_{HD25}	0.298717%	0.2987%
v_{THD}	1.09209%	1.0903%
v_{RMS}	347.536 kV	347.54 kV
Inverter Side	PSCAD	Hand calculation
v_{HD11}	0.616412%	0.6164%
v_{HD13}	0.452116%	0.4521%
v_{HD23}	0.352654%	0.3527%
v_{HD25}	0.271904%	0.2719%
v_{THD}	0.907167%	0.8847%
v_{RMS}	226.356 kV	226.38 kV

Table 2: Rectifier and inverter voltage distortion results

5.3 Power Indices

Individual and total powers (real and reactive) as well as the total apparent power are measured. A multimeter is inserted to measure the total real and reactive power (Figure 6). The developed "Harmonic Component Power Calculator Tool" (Figure 5) for individual harmonic measurements is used and the power for each frequency is obtained. The results from the developed tool are shown in Figure 12.

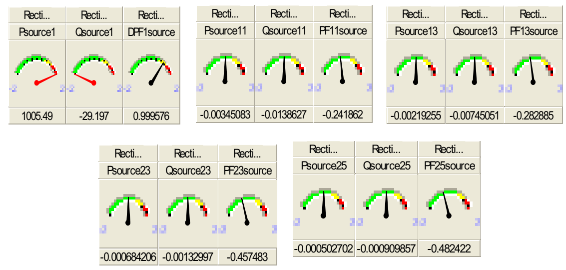

Figure 12: Power index results at the rectifier

The power index results are summed together using equations (1) and (2) and compared to the multimeter component results as shown in Figure 13.

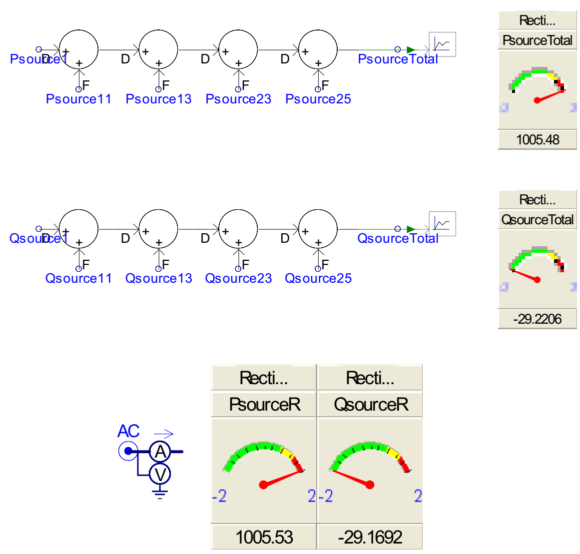

Figure 13: Comparison of multimeter results

Figure 13 shows that the developed tool gives the same results to that of the multimeter. This proves that the multimeter is measuring complex power.

5.4 Impedance Scan

An impedance scan is performed at the rectifier AC bus as shown in Figure 14. The Zscan only provides a text file output and this is a disadvantage of the software as no frequency sweep plot is directly obtained.

Authorized licensed use limited to: Cape Peninsula University of Technology. Downloaded on May 10,2021 at 06:53:57 UTC from IEEE Xplore. Restrictions apply.

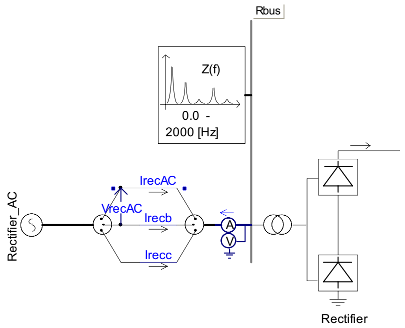

Figure 14: Impedance scan performed

An external graphic output program called "LiveWire" is needed to obtain a sweep. The "LiveWire sweep" result for the rectifier is shown in Figure 15.

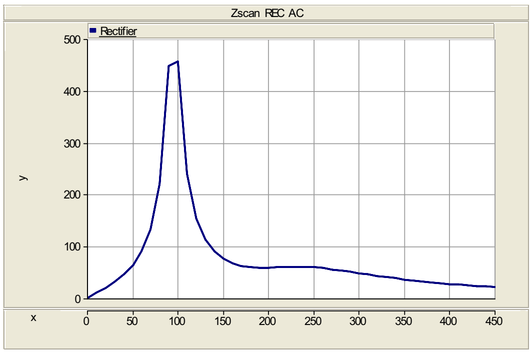

Figure 15: Impedance scan performed (rectifier bus)

When a scan study is conducted on the inverter side and plotted by "LiveWire" a similar response to the rectifier side (94 Hz) is obtained and shown in Figure 16.

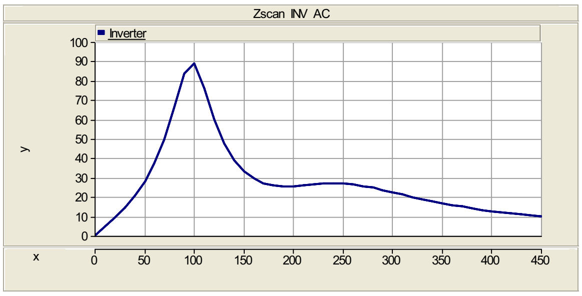

Figure 16: Impedance scan performed (inverter bus)

6 Conclusions

The toolbox in the PSCAD library was evaluated to ascertain if there are any tools available for directly generating harmonic indices. The following components were utilised (multimeter, ammeter, voltmeter, FFT, harmonic distortion, RMS component and Zscan) and used to create adaptive tools. It was found necessary to develop combined tools to directly generate harmonic indices making analysis more user-friendly and effective.

Firstly, a "Distortion Index Tool" was developed. It makes analysis more compact and easier to be accommodated on a work space. This tool can provide complex wave decomposition and provide the magnitude as well as the phase angle of the different individual components. It can also calculate the individual as well as the total harmonic distortion indices and finally produce the RMS values for a voltage or current input signal.

This was followed by the "Harmonic Component Power Calculation Tool". This tool produces the total individual harmonic real powers as well as the individual reactive powers for the specified harmonics. Finally, the "Apparent Power and True Power Factor Tool" was developed combining these indices making these measurements visible.

A case study was conducted and the application of the tools has been demonstrated. The HVDC CIGRE Benchmark network was used for the case study and harmonic analysis results were obtained on the rectifier and inverter sides. The tools were also very effective for demonstrating the harmonic mitigation techniques applied to HVDC systems.

The results were similar to hand calculation results, thus proving their effectiveness of the modelling and simulation studies.

An important factor is the establishment of resonance in a HVDC system. For this purpose the Zscan tool was evaluated. It was found that it only provides a text output file and no graphical representation of a frequency sweep versus impedance. It was further found that an external graphic program (LiveWire) can be used to generate the desired plot.

These developed tools are innovative and time saving and are recommended for use when conducting harmonic analysis on integrated HVAC/HVDC power systems.

References

[1] S. J. Ranade (Chairman, Editor), "Modelling and Simulation of the Propagation of Harmonics in Electric Power Networks, Part I: Concepts, Models and Simulation Techniques", *IEEE Transactions on Power Delivery*, **Vol.11**, No.1, pp. 452-465, (January 1996).

[2] Manitoba HVDC Research Centre. "PSCAD User's Guide" v.4.2.1. Winnipeg Canada, (2005).

[3] J. Arrillaga and N.R. Watson, "Power System Harmonics", 2nd Edition, pp. 2, ISBN: 0-470-85129-5, (2003).

[4] R.C Dugan, M.F. McGranaghan, S. Santoso and H.W. Beaty," Electrical power systems quality, MacGraw-Hill, 2nd Edition, pp.175-185, ISBN: 0-07-138622-X,(2002).

[5] J. Arrillaga, B. Smith, R. H. Watson & A. R. Alan, ".Power System Harmonic Analysis" pp 134-137, ISBN: 0 471 97548 6, (1997).

[6] M.Szechtman, T. Wess and C.V.Thio, "First benchmark model for HVDC control", *Electra*, No. 135, pp.55-73, (1991).

[7] M.Szechtman, T. Wess and C.V.Thio, "A benchmark for HVDC studies", *International conference on AC and DC power transmission*, pp.374-378, ISBN: 0-85296-517-6, (1991).

Authorized licensed use limited to: Cape Peninsula University of Technology. Downloaded on May 10,2021 at 06:53:57 UTC from IEEE Xplore. Restrictions apply.