HVDC HARMONIC ANALYSIS USING TIME DOMAIN SOFTWARE

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Abstract. The research work in this paper focuses on the evaluation and application of PSCAD time domain software for conducting harmonic analysis on integrated HVAC/HVDC power systems. Typically frequency domain software is used for conducting such studies. They however do not take the dynamic behaviour of the system components into account, only giving steady-state results. To overcome this problem time domain software is used. The PSCAD software was found to have shortcomings in its library tools in that established harmonic analysis indices are not directly generated. Where such shortcomings were found adaptive tools were developed, namely, "Compact Distortion Index Tool", "Compact Harmonic Component Power Calculation Tool" and "Apparent Power and True Power Factor Tool". These tools were applied in a case study using the CIGRE HVDC Benchmark system. Results were generated and it was found that the developed tools were effective for conducting harmonic analysis using time domain software.

Key Words: Time domain software, harmonic analysis, model development

1 INTRODUCTION

The non-linear behaviour of HVDC converters cause distorted voltage and current waveforms in the HVAC network to which it is connected. These drawbacks make it imperative to study the effect of harmonics as well as apply suitable mitigation solutions. Harmonics is a steady-state concept [1]. An integrated HVAC/HVDC system is however a time varying system and therefore traditional harmonic analysis software tools are not adequate for taking into account the dynamic behaviour of the different elements in such networks. A time domain software package is needed to conduct such studies.

Currently there is very little published on the study of 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.

No individual and total harmonic distortion indices as well as *RMS* quantities for voltage and current are available as a single tool. Also no compact tool for generating results for individual and total powers for harmonics are present. Further there is no combined tool for the measurement of apparent power when harmonics are present and there is no single compact tool to give the true power factor.

To achieve these results harmonic analysis tools in the library were utilized and combined to develop adaptive tools to obtain established index results. Thus the contribution of this paper is the development of adaptive tools to simplify harmonic analysis procedures.

2 RESEARCH STATEMENT

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

3 PSCAD SOFTWARE TOOLS

The time domain software package PSCAD/EMTDC version 4.2.1 has the following tools in its library [2].

3.1 Measuring Devices

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

The first measuring device is the multimeter. This meter can measure instantaneous voltage and current as well as *RMS* voltage (V_{RMS}) [4]:

$$V_{RMS} = \sqrt{\sum_{h=1}^{h\max} (V_h)^2} \quad (1)$$

It does not measure *RMS* current (I_{RMS}). This meter can be used both for single and three-phase and for measuring real and reactive power when harmonics are present. It can also be used to measure DC voltage and current.

The meter is connected in series at the point where the measurement is required. The meter is shown in Figure 1.

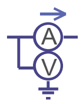

Fig. 1: Multimeter Measuring Device

This software also has dedicated meters for individual quantities (amps and volts). It comes equipped with an ammeter, line-to-line voltmeter and a phase-to-ground voltmeter. These are used as inputs to all the different harmonic analysis tools and are shown in Figure 2.

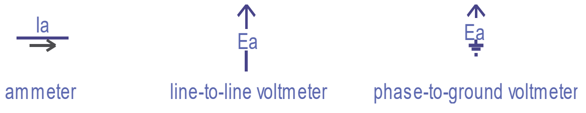

Fig. 2: Dedicated Measuring Devices

3.2 Fast Fourier Transform (FFT) Tool

To obtain the magnitudes and phase angles of the fundamental and harmonics of a waveform, the Fast Fourier Transform (FFT) tool is used.

This Fast Fourier Transform (FFT) can determine the harmonic magnitude and phase angle of the input signal as a function of time. The input signals are first sampled before they are decomposed into harmonic components. The main purpose of this tool is the decomposition of distorted waveforms (time domain into harmonic domain) to obtain individual harmonic components ($V_h\angle\theta_h°$ and $I_h\angle\delta_h°$).

The FFT tool requires an input from a measuring device and produces data outputs. In order to display the results it is necessary to combine the FFT with output channels one for each component. This tool is shown in Figure 3.

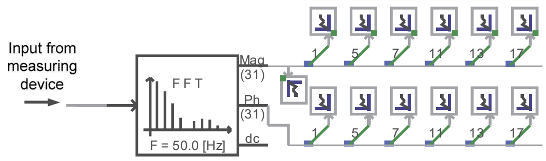

Fig 3: FFT Tool

3.3 Root-Mean-Square Index Tools

3.3.1 RMS Calculator Tool

To overcome the deficiency that the multimeter (Figure 1) is inadequate to measure I_{RMS}:

$$I_{RMS} = \sqrt{\sum_{h=1}^{h\max} (I_h)^2} \tag{2}$$

A combination of tools is required to obtain $I_{RMS.}$

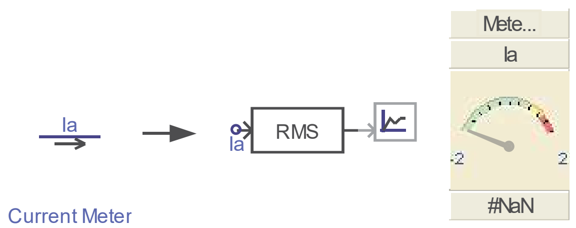

Fig 4: *RMS* Current Meter Tool

This tool will be called an *RMS* Current Meter Tool. The tool is made up of an ammeter (*Ia*) and a calculator (*RMS* calculator tool) together with an output channel and a control panel to display the results. This tool can also be applied for voltage measurement.

3.4 Harmonic Distortion Tool

For evaluating harmonic penetration the total (V_{THD} and I_{THD}) and individual harmonic distortion indices (V_{HD} and I_{HD}) of an input signal needs to be measured. The *THD* is a measure of the effective value of the harmonic components of a distorted waveform. It is the potential heating value of the harmonics relative to the fundamental and calculated by the following indices [4]:

$$\%V_{THD} = \frac{\sqrt{\sum_{h=2}^{h\max} (V_h)^2}}{V_1} \tag{3}$$

$$\%I_{THD} = \frac{\sqrt{\sum_{h=2}^{h\max} (I_h)^2}}{I_1} \tag{4}$$

The contribution to distortion by individual components is evaluated by the *HD* index:

$$\%V_{HD} = \frac{V_h}{V_1} \times 100\% \qquad (h>1) \tag{5}$$

$$\%I_{HD} = \frac{I_h}{I_1} \times 100\% \qquad (h>1) \tag{6}$$

To simultaneously measure these indices a combined tool is needed and will be called a Harmonic Distortion Calculator Tool. The main component of this combined tool is the harmonic distortion calculator and is shown in Figure 5.

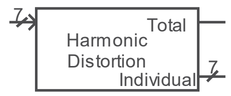

Fig 5: Harmonic Distortion Calculator

On its own it cannot be applied. Before the harmonic distortion can be quantified for a specific waveform (current or voltage) the waveform must first be put through a FFT tool and the output data is then fed to the harmonic distortion calculator. The outputs (total and individual) are then displayed on an output channel or on a bar graph (PolyMeter, Figure 12).

The developed harmonic distortion calculator is shown in Figure 6.

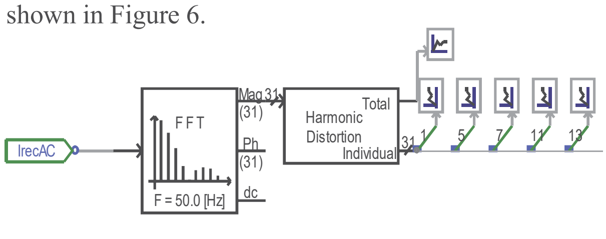

Fig 6: Harmonic Distortion Calculator Tool

Also required for harmonic penetration studies is the measurement of V_{RMS} and I_{RMS}. Instead of individual methods being used (Figure 1 and 4) it was found that a more complete tool which can do all the indices simultaneously. Thus such a tool was developed and it makes analysis more compact and this saves screen display space on a PSCAD page. 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 7 and is for a current input (similarly for a voltage input).

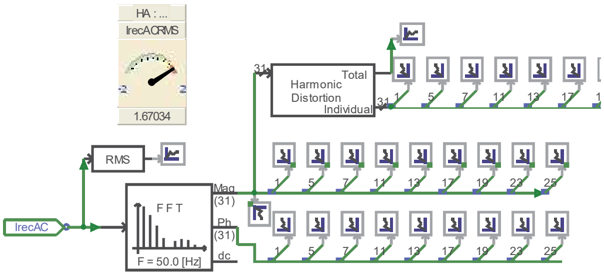

Fig 7: Compact Distortion Index Tool

3.5 Power Indices

A multimeter measures real and reactive power. These are calculated as follows [5]:

Total active power P_T (W).

$$P_T = \sum_{h=1}^{\infty} P(h) \tag{7}$$

Total reactive power Q_T (var)

$$Q_T = \sum_{h=1}^{\infty} Q(h) \tag{8}$$

A shortcoming of a multimeter 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 8. This is for fundamental frequency only. The same compact tool can be applied for all harmonic orders.

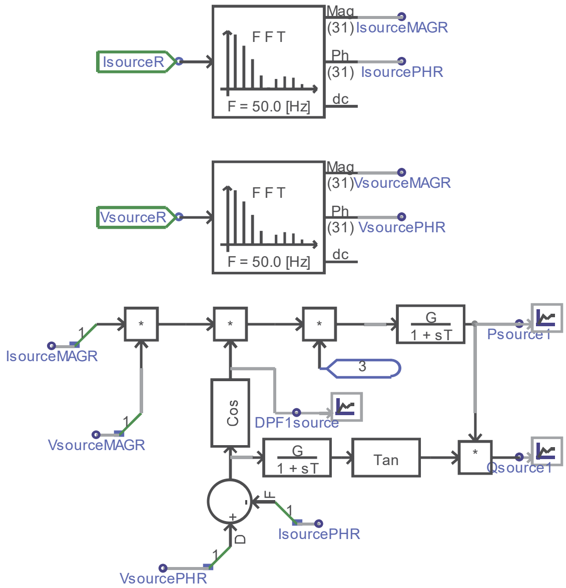

Fig 8: Compact Harmonic Component Power Calculator Tool

The voltage and current at the specific point are broken up into individual harmonic components by means of a FFT tool and are given in terms of magnitudes and phase angles. The tool applies (1) and (2) but the reactive power can also be obtained in terms of real power by means of (9) and this feature is added to the tool:

$$Q(h) = P(h)\tan(\varphi_h) \tag{9}$$

Current and voltage magnitudes are multiplied with each other as well as with the cosine of the difference between the current and voltage phase angles (which is φ_h). The multiplication of these elements produces the per-phase real power and needs to be multiplied by three to produce the total individual harmonic real power. This is fed to an integrator to eliminate ripple due to the time domain nature of the package.

The output from the integrator will produce the individual real power for the specified harmonic order. This real power is then multiplied with the tangent of φ_h to produce the individual reactive power for the specified harmonic.

When the cosine of φ_h is taken the *DPF* for the fundamental and power factor per harmonic order, $\cos(\varphi_h)$ for the rest of the frequencies are obtained. Thus the tool developed can produce individual power results for both real and reactive power as well as the *DPF* and $\cos(\varphi_h)$ power factors (Figure 8).

The multimeter 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 9):

$$S_T = V_{rms} \cdot I_{rms} \qquad (10)$$

$$PF = \frac{P_T}{S_T} \qquad (11)$$

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

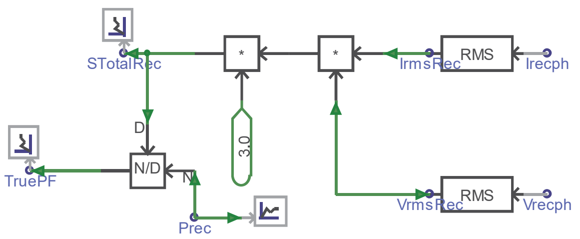

Fig 9: Apparent Power and True Power Factor Tool

3.6 Three-Phase to SLD Electrical Wire (Breakout) Tool

An essential requirement for harmonic penetration studies is that the analysis needs to be conducted on a per-phase basis. The node where the analysis needs to be conducted on the one-line-diagram must be separated into single-phases with the use of a "Three-Phase to single-line-diagram (SLD) Electrical Wire (Breakout) Tool" as shown in Figure 10.

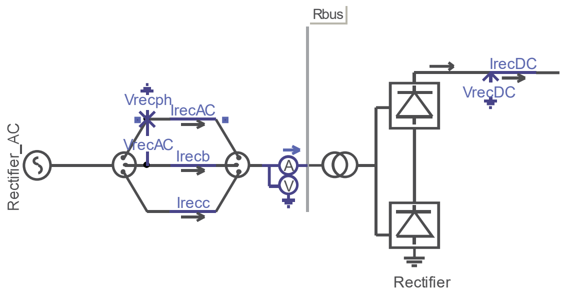

Fig 10: Three phases split into single-phase paths

This is an essential configuration for harmonic studies as all the developed tools are fed there from.

3.7 Impedance Scan Tool

To conduct harmonic resonance studies PSCAD comes equipped with an impedance scan tool, which allows the user to perform a frequency sweep at nodes in a system.

Its shortcoming is that the output data comes in the form of a text file. To obtain a sweep and see resonance points an additional tool is needed such as an external graphical analysis program (e.g. LiveWire). The application is shown in the case study.

4 CASE STUDY

The tools described in Section 3 are applied to the integrated HVAC/HVDC CIGRE Benchmark system [6], [7]. An ammeter and voltmeter are inserted in each path to measure the respective quantities and these are used as inputs to all the different harmonic analysis tools. The case study is conducted with the harmonic filters and reactive compensation installed.

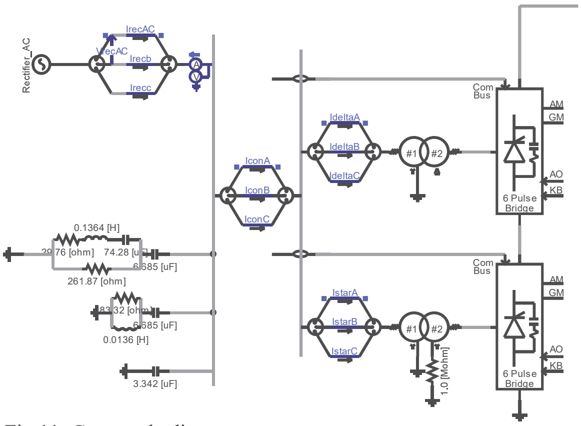

Fig 11: Case study diagram

Figure 11 shows the rectifier side. Four breakout tools are utilized to demonstrate the harmonic mitigation techniques. 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 for the four breakouts.

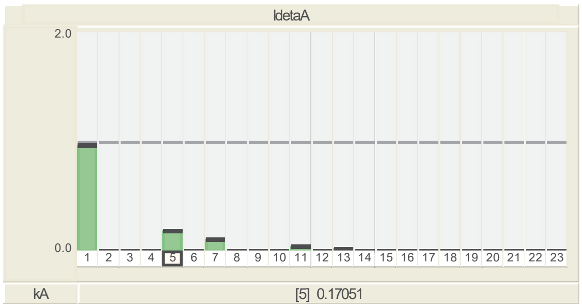

Fig 12: Harmonic analysis on the primary of the Star-Delta transformer.

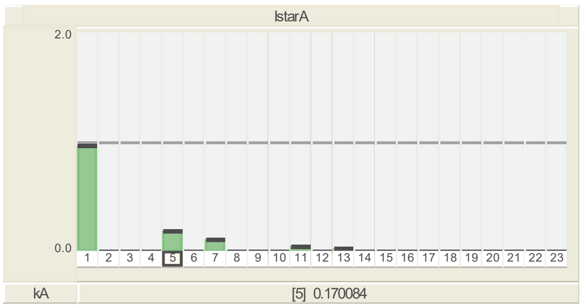

Fig 13: Harmonic analysis on the primary of the Star-Star transformer.

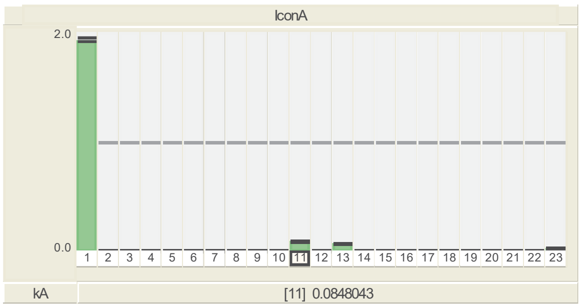

Fig 14: Harmonic analysis on the AC input side of the HVDC system.

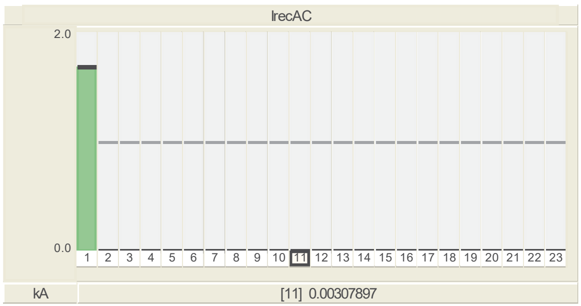

Fig 15: Harmonic analysis in the AC source path

From Figures 12 & 13 it can be seen that the converters each inject 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics. Figure 14 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 15 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:

a) Current harmonics (AC Fourier analysis including I_{HD}, I_{THD} and I_{RMS})

b) Voltage harmonics (AC Fourier analysis including V_{HD}, V_{THD} and V_{RMS})

c) Power components (individual and total powers).

d) Impedance scans (AC busbar).

4.1 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 11) is used as an input to the "Compact Distortion Index Tool" (Figure 7) 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. The FFT produces both magnitude and phase angle results and this can also be displayed on output channels as shown in Figure 16.

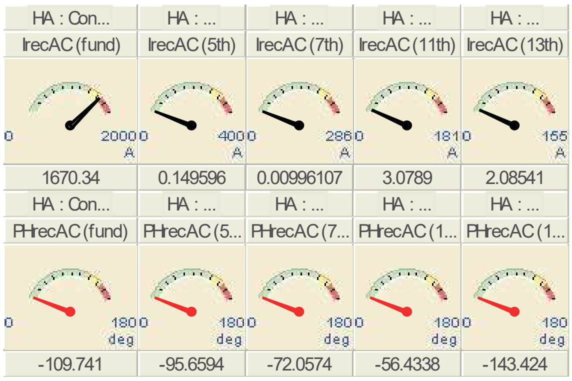

Fig 16: Rectifier AC current harmonic magnitudes

The harmonics are negligible and only the fundamental has a significant value due to harmonic filtering. The "Compact Distortion Index Tool" (Figure 7) 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.

Table 1: Rectifier current distortion results

Harmonic index results	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

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).

4.2 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 7) when applied to voltage harmonics on the rectifier side as well as the results from hand calculations are shown in Table 2.

Table 2: Rectifier voltage distortion results

Harmonic index results	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

4.3 Power Indices

Here 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 11). The developed "Compact Harmonic Component Power Calculator Tool" (Figure 8) for individual harmonic measurements is used and the power for each frequency is obtained. The results from the developed tool are shown in Figure 17.

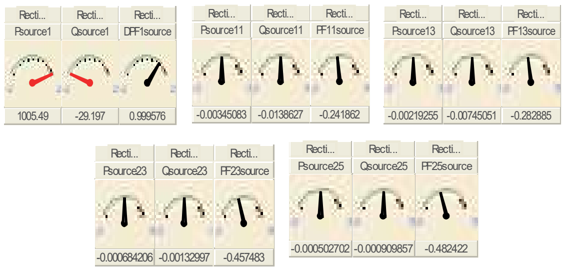

Fig 17: Rectifier individual harmonic results

To evaluate the power results obtained from the multimeter, (7) and (8) are applied using the individual harmonic components shown in Figure 17. They are summed together and compared to the multimeter as shown in Figure 18.

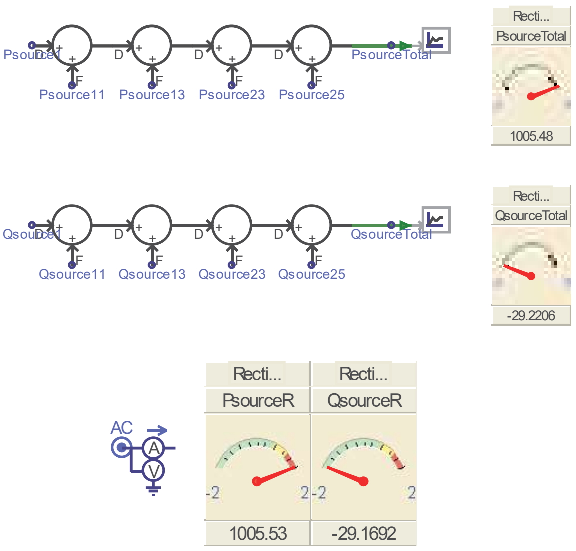

Fig 18: Comparison of multimeter results

Figure 18 show that the developed tool gives the same results to that of the multimeter. This proves that the multimeter is measuring complex power.

4.4 Impedance Scan

An impedance scan is performed at the rectifier AC bus as shown in Figure 19. The Zscan only provides a text file output and this is a disadvantage of PSCAD as no frequency sweep plot is directly obtained.

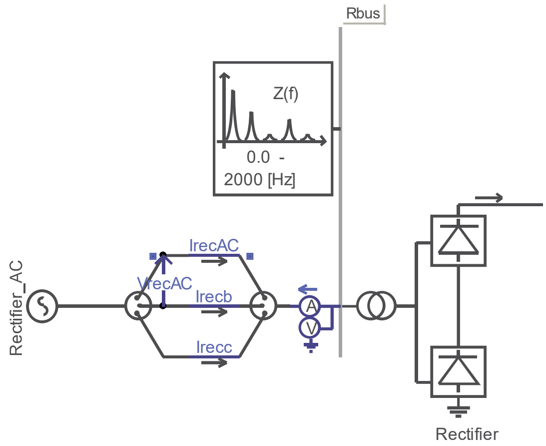

Fig 19: Impedance scan performed

An external graphic output program called "LiveWire" is needed to obtain a sweep. The "LiveWire sweep" result for the rectifier is shown in Figure 20.

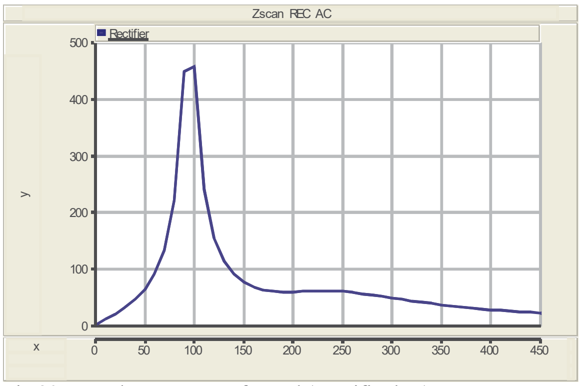

Fig 20: Impedance scan performed (Rectifier bus)

The results obtained for the AC source path of inverter side are as follows:

Table 3: Inverter current distortion results

Harmonic index results	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

Again almost similar results are obtained.

The voltage harmonic results for the inverter side are tabulated in Table 4.

Table 4: Inverter voltage distortion results

Harmonic index results	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

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 21.

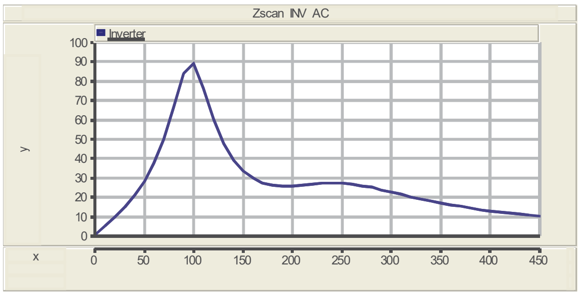

Fig 21: Impedance scan performed (Inverter bus)

5 CONCLUSIONS

When conducting harmonic analysis on integrated HVAC/HVDC power systems time domain rather than frequency domain software is found to be more suitable as it takes into account the dynamic behaviour of its components. It is also required to use established indices to assess the impact of harmonics on such a system. The toolbox in the PSCAD library was evaluated to ascertain if there are any tools available for directly generating these indices. The following measuring devices (multimeter, ammeter and voltmeter), FFT, Harmonic distortion, RMS calculator and Zscan tools were found.

When evaluating these tools it was found necessary to develop combined tools to directly generate established indices making harmonic analysis more user-friendly and effective. It was found that the following tools needed to be developed.

Firstly, a "Compact Distortion Index Tool" was developed. Its advantage is that instead of individual methods being used which clutter the work space a more complete tool which can do all of the indices in on go was more beneficial. 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 an input signal.

This was followed by the "Compact 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. Next, 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 recommended for use when conducting harmonic analysis on integrated HVAC/HVDC power systems.

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