Study and measurement of harmonics emission for the HVDC-LCC French station IFA2000.

Y.Vernay, J.Michel, JP.Taisne

***Abstract*—This paper investigates harmonics emission studies for the IFA2000 HVDC-LCC link by the use of an EMT model. Harmonic measurements have been realized in order to validate this model. The measurements and the modelling have been used to arbitrate choices of equipment replacement for transformer and filters regarding harmonics requirements. Comparisons between field measurements and modelling are presented as well as the methodology used.**

***Keywords*: Harmonics, HVDC-LCC, EMT, measurement, Filters, HVDC transformer.**

I. Introduction

High Voltage Direct Current Line Commutated Converter (HVDC-LCC) technology generates a significant amount of current harmonics whose impact on the grid has to be limited by the use of high voltage filters. Moreover, to limit as much as possible the generation of non-characteristics harmonics this type of converters requires a well-balanced AC supply voltage achieved, in part, by a low deviation between the electrical characteristics of the HVDC transformers. These phenomenon are well known and typically studied during the design stage of HVDC project but are more rarely studied for equipment replacement requiring accurate data and appropriated simulation tools.

IFA 2000 for “Interconnexion France Angleterre 2000 MW” is an HVDC-LCC link composed of 2 bipole of 1000 MW each with DC voltage +/-270 kV. This link is operating between France (Les Mandarins station) and England (Sellindge station) since 1986. A complete refurbishment of the control & protection system of the thyristors valves has been realized in 2011 by Areva T&D because of the ageing and the obsolescence of the equipment. The other power components of the HVDC substation: transformers, filters, series inductances, DC and AC switchyards typically have a longer life span so their replacement were not economically demonstrate at that time. However the ageing of these devices could affect in the next years the performance and the availability of this HVDC link. The replacement of filters and transformers are particularly critical as they are specific to the IFA2000 Les Mandarins station with a limited stock of spare parts. Also the delivery time of these equipment is very long, RTE is considering that the delivery time for an HVDC transformer is about 3 years between the start of the call of tender to the commissioning.

Fig. 1 Aerial view of the IFA2000 substation

A detailed model of IFA2000 link has been develop in EMTP-RV by RTE in order to prepare the installation of the IFA2000 control & protection system replica in RTE’s Real-Time Laboratory SMARTE [1]. This model is also used to conduce EMT studies for IFA2000 link and has been validated with comparison with real-time simulation connected to the IFA2000 control & protection replica but also with measurement from site. This paper describes the validation of this model regarding current harmonic emission and the studies realized to assess the impact of filter unavailability or transformer replacement on the harmonic performances of the HVDC station.

II. Harmonic Emission of a HVDC-LCC Convertor

Harmonic emission by HVDC-LCC converters is a well-known subject and is very well documented in the HVDC literature. Therefore the authors will just provide in this paper the minimum information and will recommend the following references for readers who search more information on this subject: [2]- [4]. As a general remark, this paper will only focus on the harmonic emission on the AC side, DC harmonic are not considered.

A. Characteristic AC harmonics

By its nature, a HVDC-LCC converter generates AC current harmonics due to thyristors commutation. Basically a converter with p pulses generates harmonic current called characteristic

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harmonic of order:

$$n = p \cdot k \pm 1 \; with \; k = 1,2,3..$$

For IFA2000 application, the 12-pulses bridge converter generates characteristic harmonics of order 11, 13, 23, 25… etc. as presented in Fig. 2.

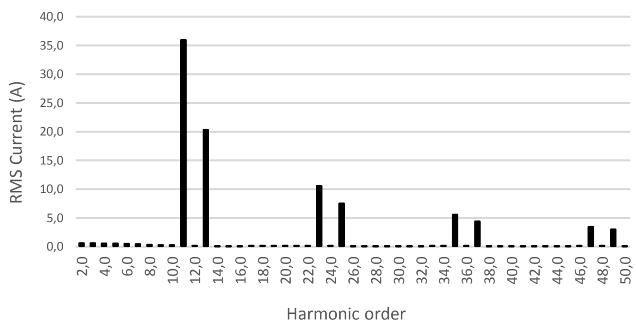


Fig. 2 Harmonic current analysis of 1 IFA2000 bipole operating at 1000MW inverter (simulation).

These characteristics harmonics are well predicted by the theory of the line-commutated converter and can be easily calculated under the following assumptions:

- The AC voltage is perfectly balanced
- There is no ripple on the DC current (infinite smoothing reactance)
- The firing of the thyristors is performed at a constant delay angle.
- The commutation inductances of the 3 phases are perfectly equals

In real-life projects, the assumptions stated above are of course not fulfilled and dedicated simulating tools and models are used to perform harmonic studies. EMT type programs are very suitable to realize these studies even if from authors' experiences other tools are more often used by HVDC manufacturer.

B. *Non-Characteristic AC harmonics*

The deviation from the assumptions above also generates harmonics of orders different from the characteristic with a much lower magnitude. To properly evaluate these harmonics the main non-ideal conditions to take into account are:

- Reactance unbalance between phases
- Reactance unbalance between bridges
- Difference in transformer turns ratio
- Firing angle asymmetry
- AC voltage unbalance.

Special efforts have be done to take into account these deviations in the EMTP model to correctly assess the full harmonic performance of IFA2000 link.

III. Modelling

RTE has developed a generic model of HVDC-LCC link tuned to meet IFA2000 characteristics. The purpose of this model was not in a first time dedicated to harmonic studies but as it shall accurately represent the steady-state and the dynamic behaviour of the HVDC link it was suitable for harmonic studies.

The control and protection system has been developed in Matlab Simulink so it can be directly imported in EMTP by the means of DLL (Dynamic Link Library). More explanation about Matlab Simulink interface can be found in [6]. The control system model contained all the relevant control loops and functions of the HVDC link according to the real control architecture of IFA2000 project as presented in Fig. 3.

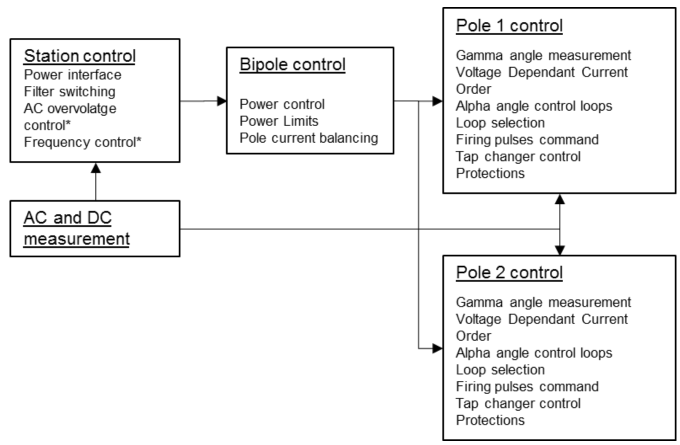


Fig. 3 IFA2000 control system model implemented

All major power system equipment of the substation on both sides are represented in the model as well as the HVDC cables. Converter pole is composed of a 12-pulses bridge. Special care has been taken to represent all the transformers with their specific measured value from factory tests to take into account the unbalances created by deviation between transformer series impedance values.

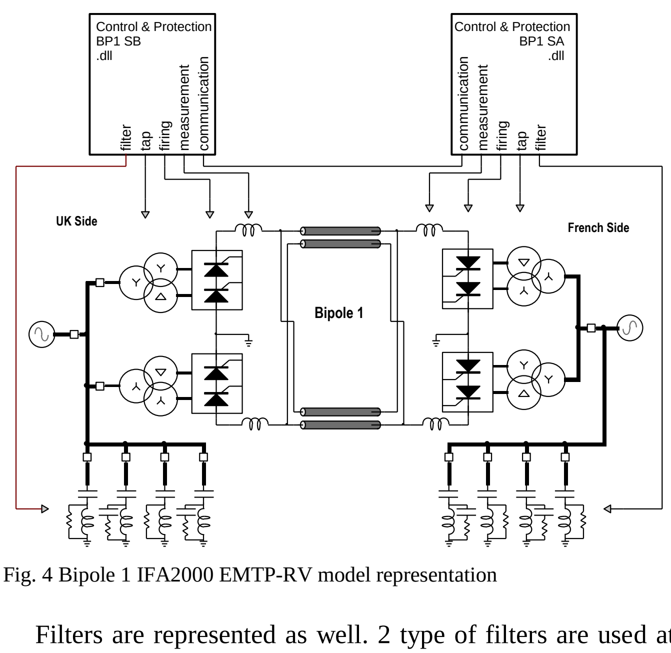


Fig. 4 Bipole 1 IFA2000 EMTP-RV model representation

Filters are represented as well. 2 type of filters are used at Les Mandarins substations: 2 PH2 filters and 2 PH3 filters are allocated per bipole to limit the emission of harmonic in the RTE 400kV grid and also to compensate the reactive power absorb by the converter. Each filter is rated at 150 MVAR and are switched as a function of the DC power in automatic mode.

IV. VALIDATION WITH MEASUREMENT

A measurement campaign has been set to verify the harmonic emission of IFA2000 link. To do so a power quality analysers has been connected to the 400 kV current transformer of Bipole 1. Another power quality analyser has been connected to the current transformer of a PH3 filter to check the correct proportion between the harmonic current from the converter and the harmonic current absorb by the filters.

The power quality analysers have been set to measure the average harmonic currents of order 2 to 50 every 10 minutes.

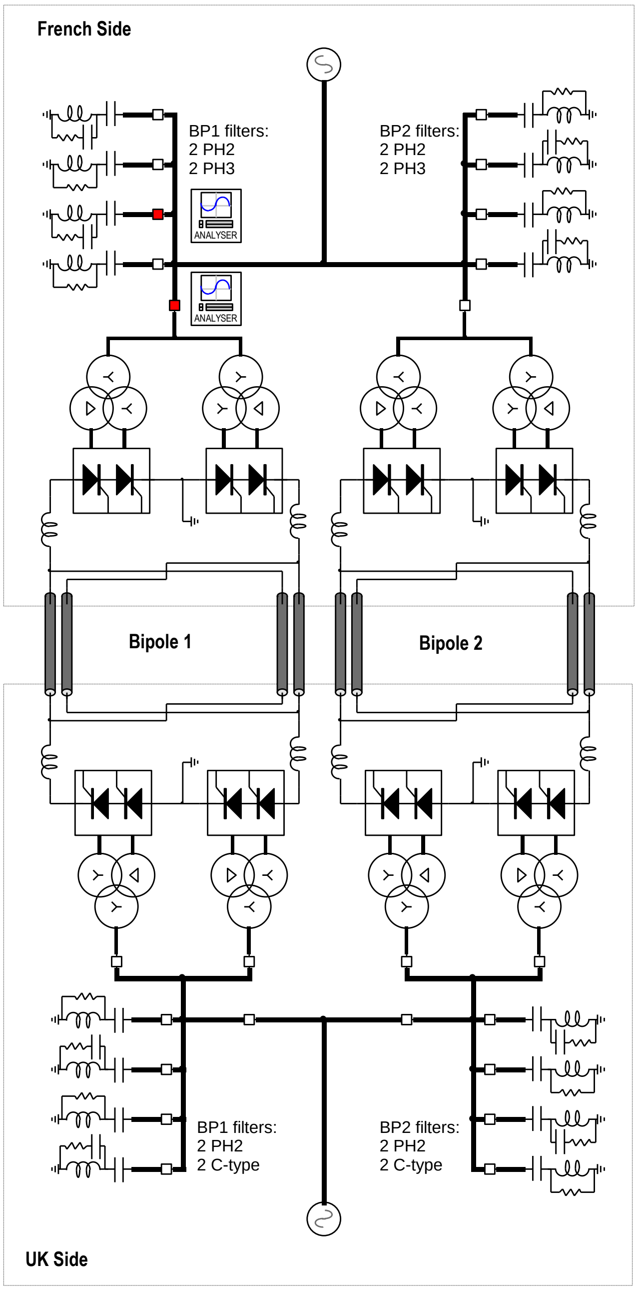


Fig. 5: IFA2000 single line diagram. In red: harmonic analyser location.

A. *HVDC Bipole measurement*

Harmonic emission vary with the DC power of the HVDC link. For this study, the author have decided to validate the EMTP model for 8 setting points: 4 level of DC power (250 MW, 500 MW, 750 MW and 1000 MW) and for both directions: rectifier and inverter. The data have been selected for these setting points and points corresponding to power ramping period have been removed. The number of measurement point selected for this study is given in Table 1. For each HVDC setpoint studied, EMTP simulations of the HVDC steady state have been realized with calculation of the harmonic emission at the end of the simulation.

Power	Converter mode	Number of measures (10 min point)
250 MW	Rectifier	85
	Inverter	27
500 MW	Rectifier	51
	Inverter	95
750 MW	Rectifier	148
	Inverter	72
1000 MW	Rectifier	3428
	Inverter	1850

Table 1 : Points selected during the measurement campaign

Harmonic measures have been cross-tabulated with data from RTE network database like: AC voltage at Les Mandarins substation, number of HVDC link in service, HVDC power per bipole, and number of filters in service.

To properly compare the harmonic with the simulation results, all measurement have been recalibrated to the nominal voltage of 400 kV. However this correction was insufficient as the position of the IFA2000 transformer tap changer is not continuously monitored in RTE database and has an impact on the AC voltage directly connected to the 12-pulses bridge converter and so to the harmonic emission.

Les Mandarins tap changer control is based on alpha or gamma angle limits depending of the mode of operation rectifier or inverter. The range of the authorised alpha/gamma angle values is set so that several tap position are possible for the same steady-state condition thus different value of harmonics are possible.

The measurement have confirmed this analyse, for one setpoint studied, different values of harmonic current can be observed. As an example in Fig. 6, for the setpoint 1000 MW rectifier, 11^{th} order harmonic current can varied about ±10% around the mean value observed.

In order to take this variation into account, all stable tap position for one setpoint are simulated in the EMTP model. The maximum and minimum harmonic value per order observed in simulation are compared to the 95 percentile and 5 percentile of the measurement. By this way, the extreme value of the measurement are note taken into account and we check that the EMTP model is able to correctly reproduce the harmonic emission observed on site.

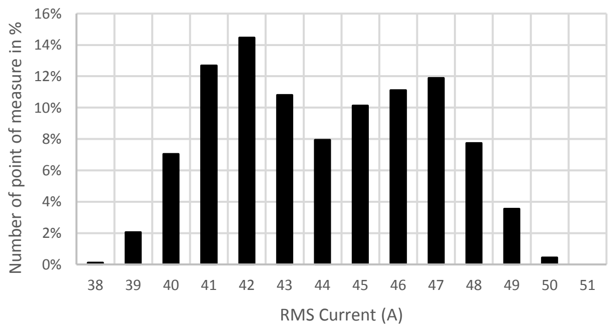


Fig. 6: Distribution of the 11th order current harmonic at bipole 1 for operation at 1000MW rectifier (measure).

1) Characteristic AC harmonics validation

This section will focus on the EMTP model validation for the AC characteristic harmonics which are the large majority of the total harmonic emission. Comparisons for 1000 MW DC power are presented in Fig. 7 and for 500 MW in Fig. 8. A good match is observed as for almost all cases the EMTP results cover and are closed to the window of the characteristic harmonics measured on site.

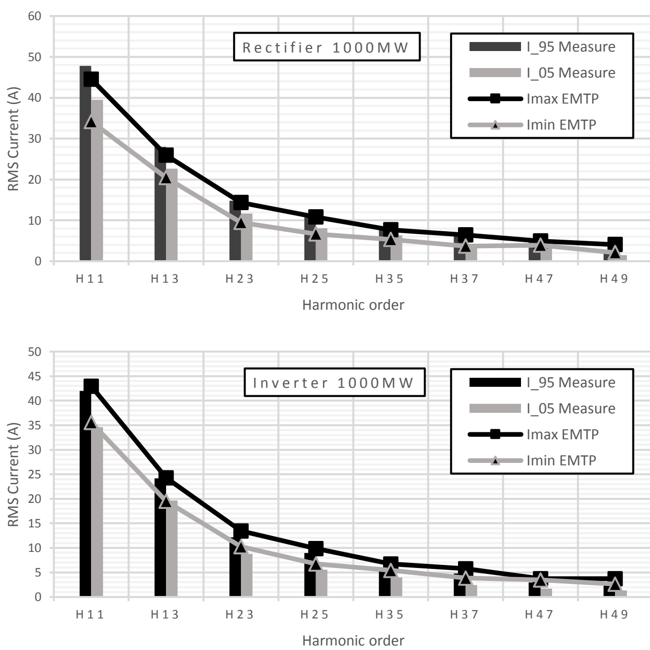
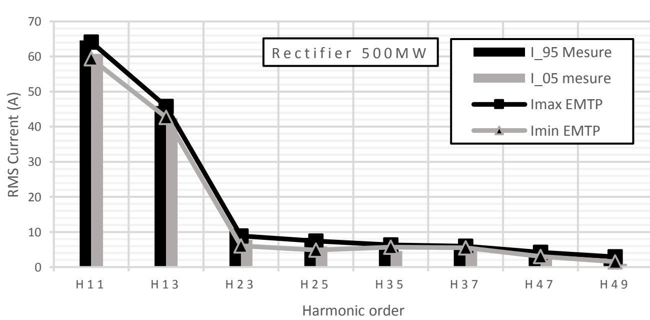


Fig. 7: Comparison model versus measurement of characteristics harmonic at 1000 MW rectifier and inverter.



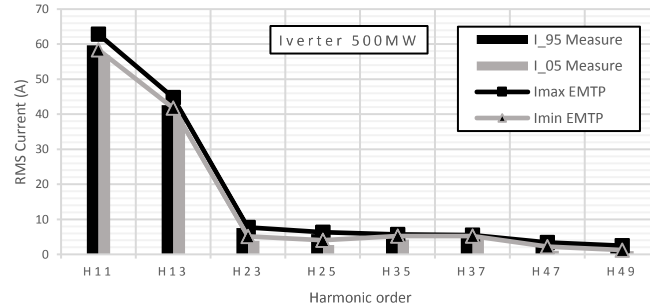


Fig. 8: Comparison model versus measurement of characteristics harmonic at 500 MW rectifier and inverter.

For some harmonics the maximum value measured on site (considered here as the 95 percentile) are higher about 2 A than the maximum value provided by the EMTP model. This has been judged as acceptable for the need of the harmonics studies.

2) Non-Characteristic AC harmonics validation

As presented in previous chapter, the estimation of the non-characteristics harmonics is theoretically much complex than for characteristics harmonic as it requires accurate data on system. The analyse of non-characteristics harmonic is also a challenge as the variation of these harmonics not only vary with controlled parameters of the HVDC link but also with external variables like background harmonics. As an example, the Fig. 9 shows the evolution of the bipole 1 current harmonic for order 5, 11 and 13 during the 08/11/2017 evening. We can observe that during this period, the bipole was operating at a constant setpoint of 1000 MW inverter with constant emission of characteristic harmonics of rank 11 and 13 while the non-characteristic harmonic of rank 5 has been multiplied by 6 during the same period.

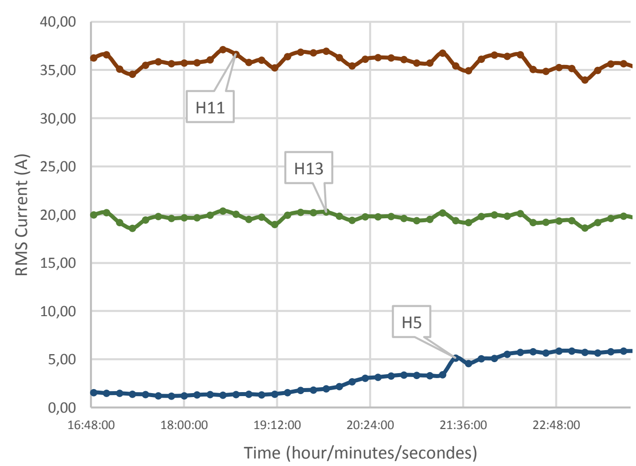


Fig. 9: Measurement of currant harmonic of bipole 1 for rank 5, 11 and 13 during 08/11/2017 evening.

This event illustrates that the AC voltage grid has a non-negligible impact on non-characteristic harmonics emission. Simulations have confirmed this observation by applying harmonic AC voltages with variation in amplitude and in phase (meaning zero crossing delay from 50 Hz signal). The AC voltage harmonics have not been measured during this campaign and the equipment used does not have the phase harmonic measurement capability. By a consequence no real validation regarding non-characteristic harmonics was hoped. However, the harmonic current measured in the filter and the PH3 filter frequency response have been used to estimate the magnitude of voltage harmonic. EMTP time domain simulations performed using this background harmonic estimation have shown results for non-characteristics harmonic in the same range of order as measurement but without notable accuracy as presented in Table 2 for 500 MW operation.

This point has been considered has a minor issue since the emission of non-charasteristic harmonics is very low compared to the total emission of harmonics. Future investigation on this topics will requires more measurement and especially information on AC voltage harmonic in magnitude and phase.

		Rectifier		Inverter	
		Measure	Model	Measure	Model
Harmonic order	H3	2,8 A	1,8 A	3,0 A	2,7 A
	H5	1,5 A	2,4 A	1,3 A	1,5 A
	H7	1,4 A	2,3 A	1,4 A	0,8 A

Table 2 : Non-characteristic harmonic validation for operation at 500 MW

B. *Filter measurement*

2 type of filters are used at Les Mandarin substation: PH2 and PH3. Each HVDC bipole used 2 PH2 filters and 2 PH3 filters in order to limit harmonic emission and to compensate reactive power consumption of the converter. Frequency responses of these filters are given in Fig. 10.

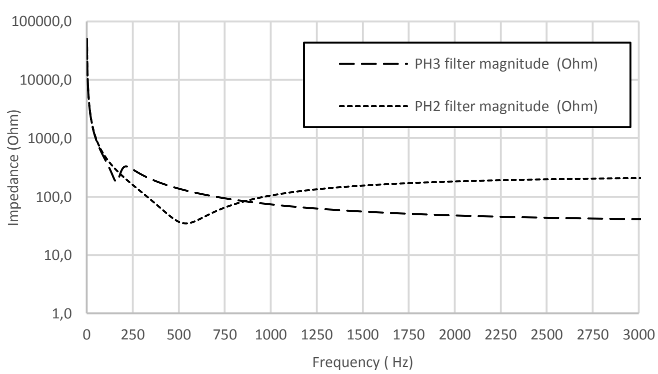


Fig. 10: Frequency responses of IFA2000 filters, French side

Another objectives of the measurement campaign was to verify the performances of IFA2000 filters for harmonic emissions. The filters have been installed more than 30 years ago and are facing ageing issue. To replace R-L-C component of the filter, measurement have been used to check if the hypothesis of the filters sizing were still valid even if the background harmonics and the grid topology have changed.

To do so, as only one bipole converter was monitored, only measurements points with symmetrical bipole operation have been selected with the hypothesis that for the same setpoint the 2 bipole harmonic emissions are equals. The status of all filters have been monitored as well, in order to estimate for each harmonic measurement points the total harmonic emission by the two bipoles and the total harmonic absorption by the filters.

First conclusion was that a much larger amount of non-characteristics harmonics are observed in the filters compared to convertor emission meaning that the filters are also loaded by the background harmonics.

Second conclusion was that filters are efficiently reducing the emission of characteristics harmonic on RTE's grid. A rigorous comparison between the harmonics generated by converter and the harmonic absorbed by filters will required more information on the harmonic phase. As explained in previous chapter this functionality is not included in the power quality analysers used during this campaign. And so, on other hypothesis taken was that all the harmonics measurement of same order share the same phase.

Based on this hypothesis, the non-filtered current harmonic emission on RTE's grid have been estimated by comparing the total harmonic emission of the HVDC and the total harmonic absorption of the filters. Fig. 11 shows the ratio of the harmonic emission on RTE's grid compared to the total HVDC harmonic emission for order 11, 13, 23 and 25 which is calculated using:

$$ratio_{I_h} = \frac{\sum I_{h_{HVDC}} - \sum I_{h_{filter}}}{\sum I_{h_{HVDC}}} \qquad \text{for h=11, 13, 23 and 25}$$

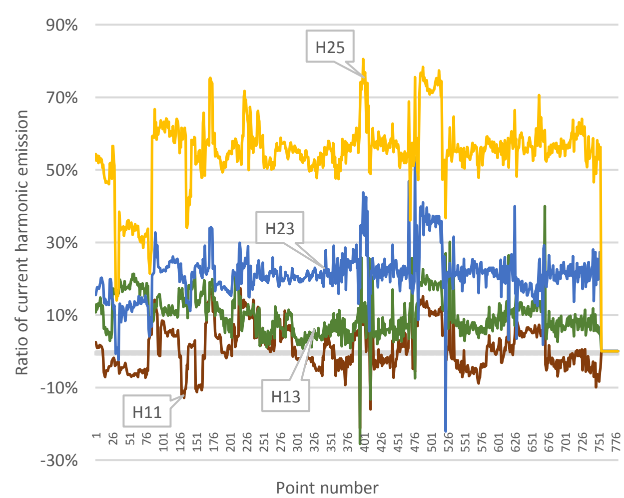


Fig. 11: Ratio of characteristic harmonics emission of order 11, 13, 23 and 25 on RTE's grid during one week (12/2017).

Harmonic order 11, 13 and 23 represent the main part of the total harmonic emission and are efficiently filtered as only a small percentage of the global emission is injected on RTE's grid. Negative values observed at some periods for orders 11 and 13 suggests that the filters also absorb background harmonics from the RTE's grid.

However, harmonic of order 25 is poorly filtered as about 60% of the emission from the HVDC converter is injected on RTE's grid.

An explanation is given by the observation of the harmonic impedance of RTE's grid at Les Mandarins, see Fig. 12, for a standard network topology calculate using an EMTP model of the full 400 kV French network and parts of 225 kV networks as described in [6]. An anti-resonance of 10 Ω is observed at 1250Hz reducing the impact of the filters which have a similar total impedance at this frequency.

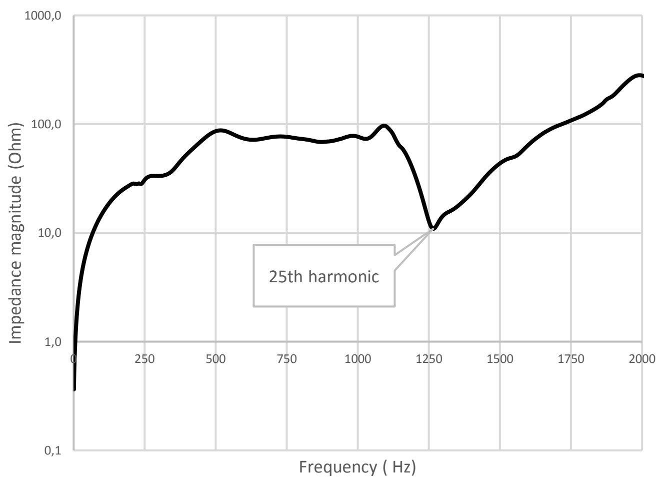


Fig. 12: 400kV grid harmonic impedance at Les Mandarins converter station.

V. Impact of transformer replacement

Single phase three windings transformers are used at IFA2000 Les Mandarins station. Each pole is connected to 3 transformers. In total, the 2 HVDC bipole used 12 transformers plus 1 transformer as a spare part. Because of the ageing of the transformer, the opportunity to purchase a second spare transformer have been studied.

The transformers currently used at Les Mandarins have all been manufactured in the same factory with the same construction drawings. Therefore the series impedances of the transformers are very close from each other with a maximum deviation from the mean value of 0.75%. As seen in previous chapters, this balance configuration permits to efficiently limit the generation of non-characteristics harmonics.

Transformer standard [7], specified that a tolerance of 10% on the series impedance is acceptable for transformer with more than 2 windings. EMTP model of the IFA2000 link has been used to assess the impact of a new transformer with a higher deviation of the series impedance regarding harmonic emission. From RTE’s experience, higher accuracy on the series impedance can be achievable by transformer manufacturers. The objective of the EMTP study was to determine the acceptable tolerance value.

Parametric studies have been conducted applying the variation set of parameters described in Table 3.

Parameters	Variation	Number of cases
Power direction	Rectifier/inverter	2
Power level	250, 500, 750 and 1000 MW	4
AC voltage negative sequence	Ui/Ud < 1,5%	5
Series impedance tolerance of new transformer	|ΔZ|/Znom < 10%	100
Total		4000

Table 3 : Parametric study data for a 10% tolerance for the new transformer series impedance

Different value of tolerance have been studied: ±5%, ±7.5% and ±10%, as well as different strategy of transformer replacement: only one transformer or 3 transformer of the same pole. In case of multiple transformer replacement the same tolerance from the specified series impedance is applied but the deviation between the new series impedances is limited to 3%.

The results have been compared with RTE’s harmonic emission requirements showing that a strategy with only a replacement of only one transformer replacement is possible, avoiding the large extra investment of 3 transformers (3 transformer for one pole and a spare transformer). Also a tolerance of ±5% is recommended at least for the nominal tap of the transformer.

VI. Conclusions

This paper has described the EMT modelling of IFA2000 link and its validation for harmonic emission studies. Main conclusions are:

- EMTP model is very suitable to conduct harmonic studies for IFA2000 HVDC link.
- Cross-tabulated database and post treatment measurement data is necessary to ensure a good comparison between simulation and measure.
- Non-characteristic harmonics require detailed measurement method for proper analysis and comparison with simulation.
- EMTP model has been extensively used for a better understanding of the harmonic emission of the HVDC link and to plan future equipment replacement (transformer and filters) regarding harmonic issues.

VII. References

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