Determination and evaluation of a Harmonics In Adjustable Speed Drives

Amit Wankhade , Anil Kumar Chaudhary ,C.Veeresh

Mandsaur Institute of Technology, Mandsaur
Amitwankhade8@gmail.com

Mandsaur Institute of Technology
Madhya Pradesh, INDIA
anilkumar6352@gmail.co

***Abstract*–A large diversity of solutions exists to reduce the harmonic emission of the 6-pulse Adjustable Speed Drive in order to fulfill the requirements of the international harmonic standards. Among them, new types of advanced harmonic filters recently gained an increased attention due to their good harmonic reduction performance at the same time with small costs and engineering. In the event that such filters are used to replace existing solutions, the assessment of the harmonic performance before commissioning is a necessity. This assessment is possible by using software tools to compare the performance of different topologies. This paper presents a method to integrate the model of the filter into an existing harmonic calculation toolbox dedicated for harmonic analysis on the 6-pulse converter. The results are linked together into a practical PC software toolbox for harmonic estimation. By using a combination of a pre-stored database and new interpolation techniques the toolbox can provide the harmonic data on real applications allowing comparisons between different mitigation solutions.**

Keywords*–*variable speed drive; harmonics analysis; load flow analysis; power system harmonic; software tools.

I. INTRODUCTION

The most used front-end topology for the ASD's is still the 6-pulse diode rectifier, due to well-known advantages such as, high efficiency, low cost, robustness and reliability. Nevertheless, the major drawback of this type of ASD is the emission of the harmonic currents, which imposes different approaches to minimize this pollution. Many choices exist for the 6-pulse ASD’s such as adding line reactors, passive harmonic filters, harmonic traps, active filters, etc.

Lately, due to the development in magnetic materials and technology new types of passive harmonic filters (hereafter referred to as advanced harmonic filters or AHF) were possible to develop. Thus, even in non-ideal supply voltage (e.g. unbalance, voltage pre-distortion) these types of harmonic filters ensure Total Harmonic Distortion (THD_i) values close to or better than 5%. Therefore, many applications currently in use can replace the common line reactors with such advanced harmonic filters if the cost-performance balance leans to a positive investment.

From an engineering point of view the first attempt is to evaluate on a comparative scale the harmonic performance of all potential solutions for the investment. However, such comparisons require large experience and knowledge especially in the design phase to compare which of these solutions is better for a given case, in respect to harmonic mitigation.

Unfortunately, even though the six-pulse diode rectifier has a very simple circuit topology, the calculation of the harmonic currents is not a trivial task [1] – [7]. Moreover, a little lack of knowledge with respect to the system can make the estimation of the harmonic current far beyond a simple engineering problem.

This paper describes the development of calculation tools for harmonic estimation on the AHF. The work is then integrated with the conclusions obtained from a previous study [15] regarding the calculation of the harmonic currents on the 6-pulse drive and the results are linked together into a single toolbox. Thus, the new toolbox can provide the support for comparing different power system topologies or different harmonic mitigation solutions (e.g. an already installed line reactor compared against a new AHF).

The results are compiled into a practical PC software toolbox for harmonic estimation on real applications. Comparisons between the toolbox results and real measurement validate the implementation.

II. PRINCIPLE OF TOOLBOX DEVELOPMENT

Supported by the conclusions and experience of [16] it is chosen to let the harmonic calculation toolbox be based on a table-based model. Harmonic data, which are collected by simulations, are pre-processed and saved into databases. Furthermore, analytical expressions are used to reduce the data size where applicable. In this way, the developed tools can meet the initial goal of having a practical and convenient method to be implemented into PC software.

In a previous study [15] the focus was on analyzing only the 6-pulse drives. The achievement of this paper is extending the initial study by adding the AHF model; therefore the description of the implementation will be also provided herein.

The toolbox is developed based on a typical power system diagram as shown in Fig. 1a. This includes a transformer, two sections of cables, a linear load at the point of common coupling (PCC) and multiple connected ASD's in parallel at the customer site (hereafter referred as Panel-point).

Instead of using a large and laborious harmonic analysis, the approach used in [15] and still maintained in this study is to "split" the original diagram into multiple simple diagrams, as shown in Fig. 1b.

Each system contains an equivalent model of the power system and one single ASD. The ASD is separately analyzed using circuit simulators to obtain the line-side harmonic currents, and then all data are minimized and stored in databases for off-line estimations later in the developed toolbox. In the actual study the simulations also include the connection of the advanced harmonic filter to the ASD.

Once the harmonic currents are known for the individual ASD the superposition principle is used to regroup the original diagram. The superposition principle makes use of a compensation factor that is necessary due to the non-linearity created by the reciprocal influence when many drives are connected in parallel which will not be explained here, but more details can be found in [15].

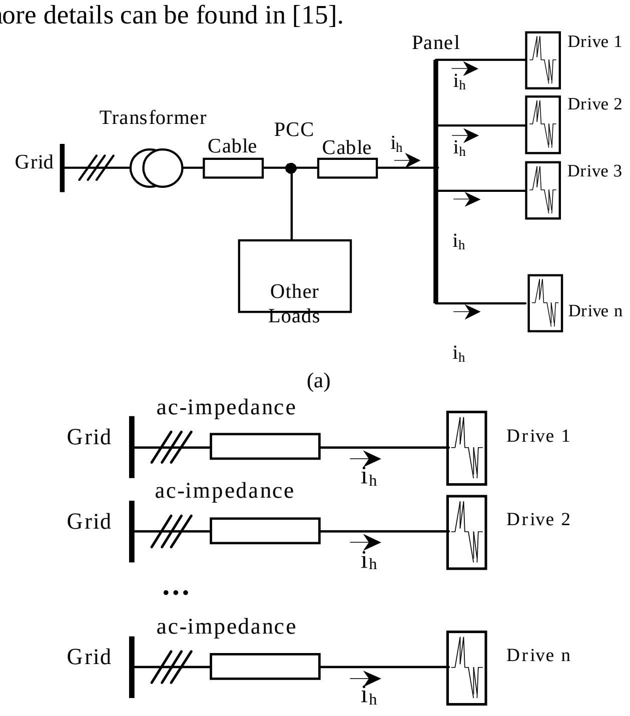

Fig. 1. System diagrams used in
a) harmonic toolbox analyzes, b) individual study approach.

Ultimately, harmonic data and all analytical expressions are compiled using Matlab programming into a graphical interface application where the user provides the input parameters. Thus, for a given case the input parameters are used to search the database retrieving for the best-fitted information and estimating the harmonic currents based upon an interpolation algorithm.

III. Data Analysis

As initially mentioned the toolbox uses for estimating the current harmonics a look-up table-based method. Therefore all harmonic data have to be achieved in advance. This section describes the line-side harmonic current emission for the topology of AHF connected to the 6-pulse ASD.

The line-side harmonic currents are evaluated as functions of two parameters, the cable impedance (further referred to as L_{ac}) and the load (R_{Load}).

$$i_{h(AHF \quad ASD)} \quad f(L_{ac}, R_{load}) \tag{1}$$

Fig. 2 shows the connection of the AHF to the 6-pulse drive.

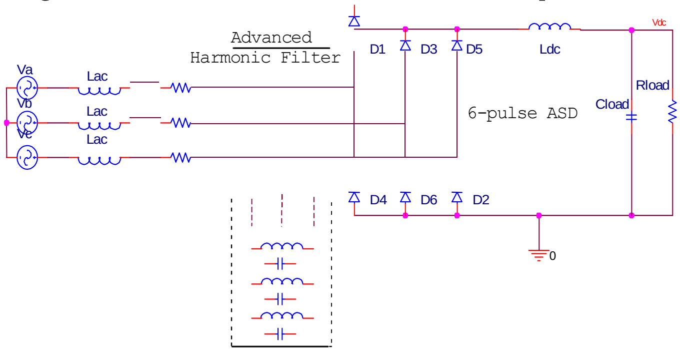

Fig. 2. Simulated diagram of Advanced Harmonic Filter (AHF) connected to the 6-pulse ASD.

These parameters are selected on an initial investigation to keep the same conditions as for the 6-pulse ASD alone simulations [15], which have the next expression.

$$i_{h(ASD)} \quad f(L_{ac}, L_{dc}, R_{load}) \tag{2}$$

These arguments are expressed on a per unit basis of an initially established nominal power. Then simulations have been run independently varying one parameter and keeping the other constant:

ac-reactance L_{ac}, between 0% to 25% p.u.,
load R_{Load}, between 10% to 160% of nominal load.

It is worth to mention that eq. (2) of the ASD alone includes also the L_{dc} term, which is used to cover different application cases, dependent on the user selection. However, in the actual case with the AHF connected to the ASD the L_{dc} is set to a value of 3%, as a default value for the internal dc-link inductance of the ASD.

The results are the harmonic currents up to the 50^{th} harmonic. Thus, based on the specified assumptions the harmonic currents can be expressed depending on these two input parameters.

Simulating the AHF connected to the 6-pulse ASD reveals that the line-side harmonic currents will decay with the increase of the L_{ac}. The load R_{Load}, however, has not a monotone effect on the harmonic currents. Fig. 4 presents the line-side 5^{th} harmonic current of the diagram in Fig. 2 (the harmonic currents are expressed in percentage of the fundamental current). It is known that a "no-load" situation produces a high distortion factor of a typical value of 40%-60%.

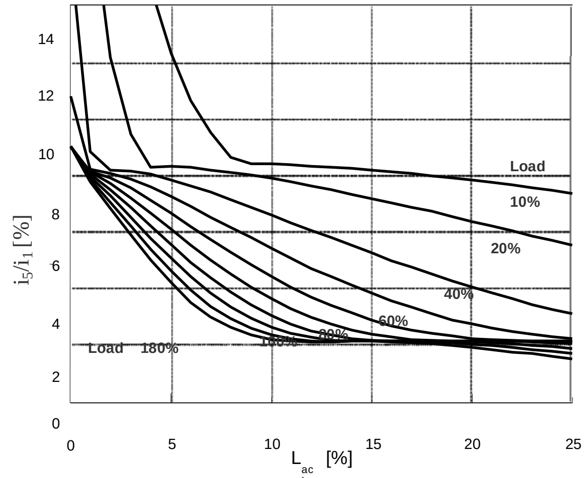

Fig. 3. Simulated 5th harmonic current with respect to the load variation and L_{ac} for the ASD alone.

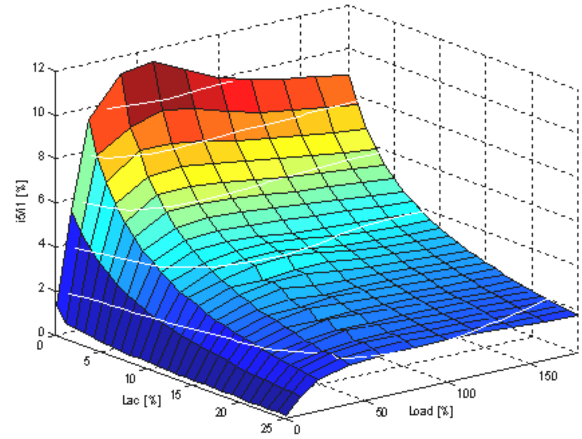

Fig. 4. Simulated 5th harmonic current versus load and ac-inductance L_{ac} for the 6-pulse ASD with the AHF.

In the case of the AHF connected to the ASD it can be noticed that a light or "no-load" situation does not produce an increase of the harmonic current (as in the ASD alone) and on the contrary it reduces the harmonic currents to almost zero value.

All other harmonic currents of this simulated diagram (AHF connected to the 6-pulse ASD) have similar shapes as the 5th harmonic shown in Fig. 4, although having lower amplitudes. Expressing the harmonic currents as a function of two parameters (L_{ac} and R_{Load}) as in Fig. 4 creates a large database requirement especially if all characteristic harmonics need to be stored up to the 50th for example.

Using an interpolation algorithm and analytical expressions in the toolbox can minimize this high amount of data. Therefore, the effort of finding such approach is highly motivated.

The only exceptions are, however, with the 5th and the 7th harmonic currents, which are typically the weightiest harmonics in the current distortion. An approximation of these with analytical expressions could increase the estimation errors. As a result, the 5th and the 7th harmonic currents are stored as tables without further reduction.

Instead, higher harmonics (starting with the 11th harmonic) are suitable for an analytical approach because they have much lower values. Thus, the approximation will not affect too much the overall performance but will bring the advantage of minimal data storage.

As Fig. 4 shows, the harmonic current looks to have an exponential decrease with respect to the L_{ac}, therefore it can be expressed as in (3), depending on an initial value (which is $i_h(0,Load)$) and an exponential function (which is $e^{-f(Lac)}$).

The argument of the exponential function ($f(L_{ac})$) was initially verified using a simple linear expression like "x/k", as in (4), where k is an empirical constant.

The results of the approximation can be seen in Fig. 5. It is noticeable that a large error exists between the simulated and the estimated characteristics.

$$i_h(L_{ac}, Load) \quad i_h(0, Load) \quad e^{\ f(L_{ac})} \tag{3}$$

$$f(L_{ac}) \quad f(x) \quad \frac{(x)}{k} \tag{4}$$

where: i_h is the harmonic current (greater than 11th),
Load is the new load of the drive, in percentage,
$L_{ac(nom)}$, is the per-unit ac-inductance,
k is an empirical constant.

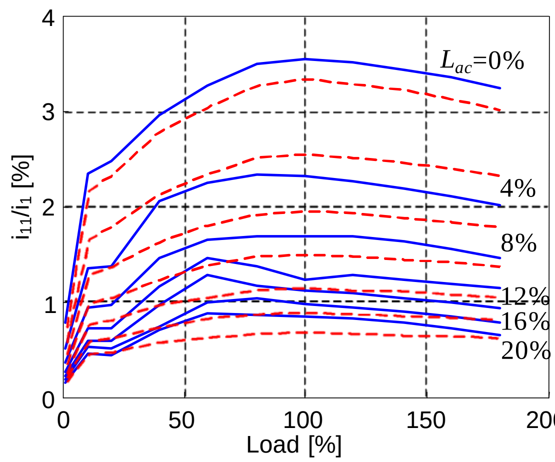

Fig. 5. Simulated and estimated 11th harmonic current from the AHF in respect to the load variation.

Since this approximation is not very accurate for a certain domain of the L_{ac}, further investigations are done by adding a quadratic function to the linear exponent, as in (5). Thus, a better approximation is achieved.

$$f(L_{ac}) \quad f(x) \quad \frac{[(x) \quad (a \ x^2 \quad b \ x \quad c)]}{k} \tag{5}$$

where: *a*, *b*, *c*, *k* are empirical constants.

Fig. 6 shows the resultant function after the addition to the initial linear function of the quadratic expression.

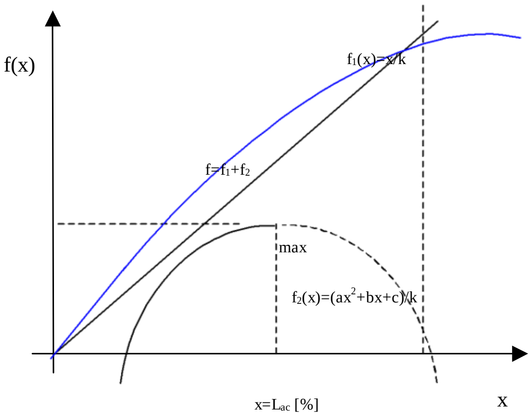

Fig. 6. Analytical expressions found for the exponential part of the harmonic current.

After finding the values of the empirical constants (*a*, *b*, *c*, *k*) the function (3) is again compared against the simulated harmonic currents. Fig. 7 provides the comparison of the simulated and estimated 11th harmonic currents. Solid lines represent the 11th harmonic currents as a function of the L_{ac} and load. Dashed lines represent the current estimation using (5) and the harmonic current curve for the L_{ac} value of 0%.

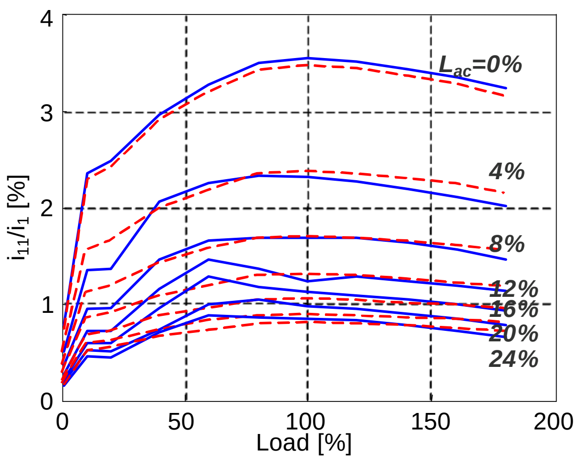

Fig. 7. Simulated and estimated 11th harmonic current from the AHF in respect to the load variation.

Thus, the study developed in this paper concludes that the harmonic currents from the analyzed circuit (AHF connected to the ASD) can be obtained as initially assumed in (3) but without the requirement of storing two-dimensional dependences. Thus, only one dependence (the values of $i_h(0,Load)$) is saved in the database while the other dependence (of the ac-impedance L_{ac}) is analytically reconstructed using (5).

The presented approach has the advantage of being compiled into one function. Then, the function is identically used for estimation of all higher harmonic currents.

In this way, the initial desire to keep minimum data for storage and a simple implementation for analytical expressions can be fulfilled, and simultaneously having the harmonic estimation at an acceptable accuracy.

IV. Toolbox Verification

The first tests were conducted with a laboratory setup illustrated by the diagram in Fig. 8. The setup consists of a 3-phase ASD supplying a resistive load of 240 with a dc-side smoothing capacitor of 200 F. The ASD was connected to the local power supply of 400 V nominal voltage and 50 Hz frequency, which has a grid impedance measured with a value of 8%. The Advanced Harmonic Filter used here (product code Danfoss AHF010) has the performance of reducing the THD_i to 10%.

The system has the possibility of connecting the ASD with or without the AHF filter. This possibility gives the chance to obtain the results in two cases, which can be verified by the implemented toolbox.

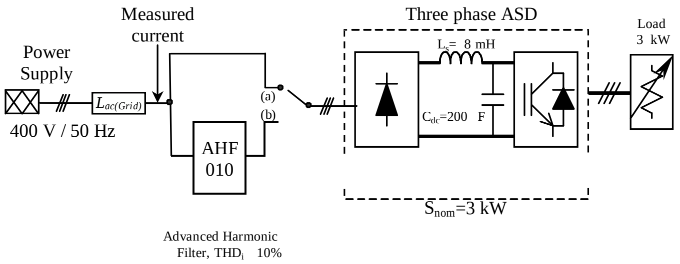

Fig. 8. Circuit diagram with the AHF010 connected to ASD.

Two experiments are performed in order to validate the toolbox implementation. The first one involves the ASD alone with the switch in position (a) and the second experiment adds the AHF to the ASD by selecting the switch in position (b). The toolbox uses the same data as inputs to the calculations. Both harmonic voltages and currents are recorded from these measurements and displayed in Table I, together with the results from the harmonic toolbox.

Table I. Comparison of laboratory measurements and harmonic toolbox results.

Harmonic order h	**Measured ASD [%]**	**Toolbox ASD [%]**	**Measured ASD+AHF [%]**	**Toolbox ASD+AHF [%]**
i_5	22.7	21.0	7.2	6.3
i_7	6.9	7.8	3.4	4.2
i_{11}	3.7	4.3	1.6	2.4
THD_i	23.9	23.5	8.8	8.3
v_5	1.7	1.6	1.0	0.5
v_7	0.9	0.8	0.8	0.4
v_{11}	0.2	0.6	0.5	0.4
THD_v	2.1	2.1	1.2	1.0

In this particular case all relevant data are exactly known and the experiment can be easily controlled and measured. The toolbox calculations are therefore as expected very close to the actual measurements as shown in Table I.

V. Design Case

In the final toolbox - Danfoss VLT MCT 31 Harmonic Calculation - the used Matlab code has been compiled into a dynamic link library (DLL) and is called by a user friendly graphical interface as shown in Fig. 9. All internal results are written out to a harmonic analysis report in Rich Text Format.

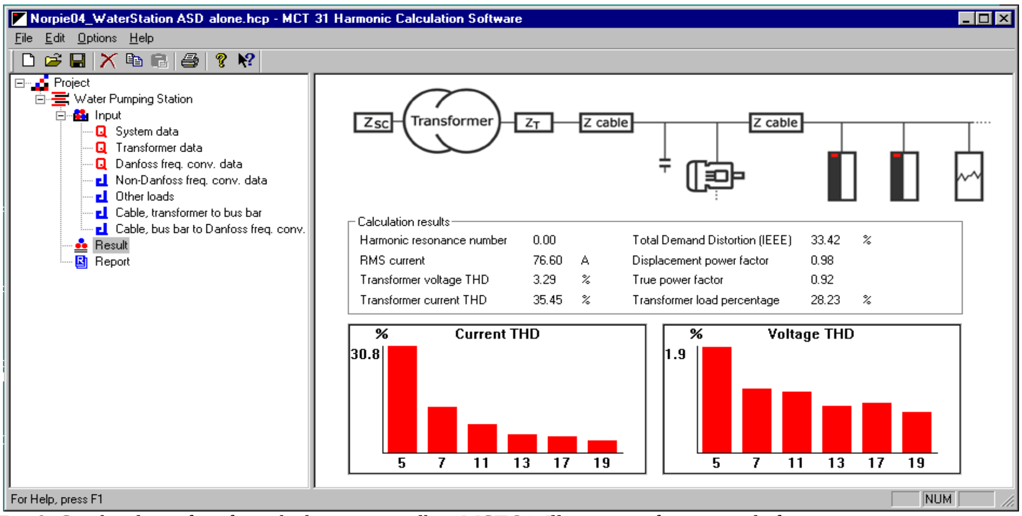

Fig. 9. Graphical interface from the harmonic toolbox MCT 31. Illustration of a case study for a water pumping station.

It should be mentioned that despite that the toolbox is designed for calculation with Danfoss ASD's only (both with 6-pulse and harmonic filters) it is also possible to make the calculations with non-Danfoss ASD's as long as the drive parameters are known.

In order to determine the accuracy of the approach, the toolbox has to assure similar results as real measurements, thus certifying both, the acquired database from simulation and the implemented algorithm.

The verifications were developed in the way of providing comparison data between a real case application of a 6-pulse ASD and the prospect of using non-expensive solution for harmonic mitigation. The operation is motivated by the intention of minimizing the harmonic currents; therefore different solutions are investigated including:

- adding ac-coils of a total value of 3%, placed in front of the 6-pulse ASD,
- using an AHF010 with a performance in THD_i of 10%,
- using an AHF005 with a performance in THD_i of 5%.

The application is a water pumping station with only a single 6-pulse ASD, as it can be seen in Fig. 10.

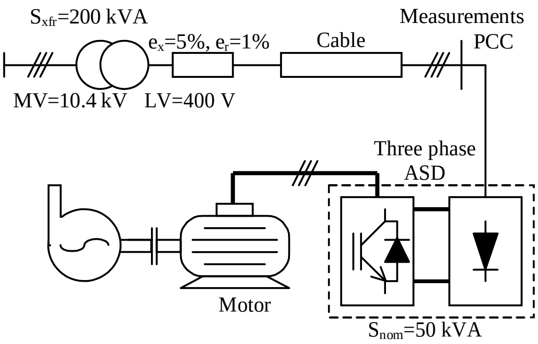

Fig. 10. Circuit diagram of the water pumping station with ASD.

Typical for an application like this, only limited data are available. The supply transformer has a nominal power of 200 kVA with an impedance of 5%. The cable between the transformer and the ASD is approximately 10 m. The input power of the ASD is measured to 48 kW. The dc-link inductance is approximately 3%, while the value of the dc-link capacitor is 26.5%.

Table II compares the actual measurements with the results of the toolbox. As it can be seen the toolbox results match the measurements with a differences of a maximum 0.8% for the THD_v, which comes mainly from the high background distortion.

Then, the harmonic calculation toolbox is further used to provide comparisons of the aforementioned possible solutions. Table III provides such comparison by giving the current and voltage Total Harmonic Distortion (THD_i, respective THD_v). Furthermore, the harmonic currents and voltages are displayed, as a result of the toolbox calculation, in Fig. 11.

Table II. Comparisons of measurements and toolbox results.

Harmonic order h	Measured ASD [%]	Toolbox ASD [%]
i_5	32.0	30.0
i_7	13.8	13.0
THD_i	37.0	35.3
v_5	2.1	1.9
v_7	1.2	1.1
THD_v	4.2	3.4

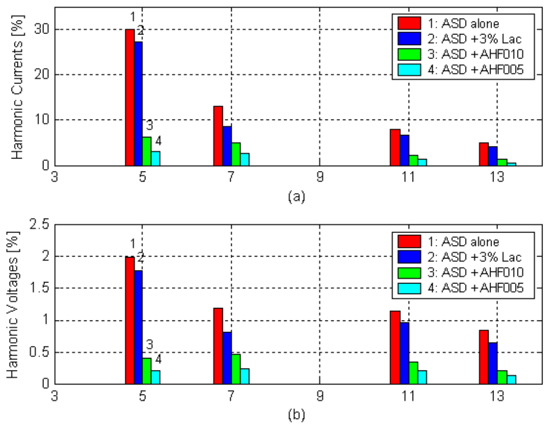

Fig. 11. Toolbox harmonic results with the proposed solutions for the water pumping station. a) Harmonic currents. b) Harmonic voltages.

Table III. Comparisons of the harmonic indices (THD_i and THD_v) for the proposed solutions and the actual measurement at full load.

Harmonic indices	Measured ASD alone [%]	Toolbox ASD alone [%]	Toolbox ASD + 3% L_{ac} [%]	Toolbox ASD + AHF010 [%]	Toolbox ASD + AHF005 [%]
THD_i	37.0	35.3	29.7	8.6	4.4
THD_v	4.2	3.4	2.5	1.0	0.5

Now it is clear how to select the harmonic mitigation solution toward the best performance device and maybe some other criteria. However, the customer could decide for using an usual L_{ac} line-impedance, but the value of the L_{ac} should be increased more than 3%, in order to reduce even more the current THD_i. This increase could lead to a bigger size and a considerable voltage drop on the L_{ac}, which could not be tolerated in certain cases. Maybe the AHF010 solution can provide a better THD_i but installing the AHF005 solution is the best choice for this case if the goal is minimum THD_i.

VI. Conclusion

The main focus has been on analyzing the harmonic currents from an advance harmonic filter. These harmonic currents prove to behave in a similar manner with respect to the load and the ac-impedance variation. Thus, the harmonic currents can be expressed as analytical functions, which help reducing the amount of the stored data. This conclusion facilitates an easy and fast integration of the multi-pulse drives into an existing PC-based toolbox application, developed originally for the 6-pulse drive.

Thus, comparative analysis can be run with different converter types in the same system conditions. The results obtained can help in choosing the appropriate topology for a given case.

Finally, the approach is validated by real measurements with satisfactory results, leading that the harmonic calculation toolbox can be used for designing new and improving existing installations with ASD's.

References

[1] W. F. Ray, “The Effect of Supply Reactance on Regulation and Power Factor for an Uncontrolled 3-Phase Bridge Rectifier with a Capacitive Load”, IEE Conf. Publ. No. 273, 1986, pp. 523-526.

[2] W. F. Ray, R. M. Davis, I. D. Weatherhogg, “The Three-Phase Bridge Rectifier with Capacitive Load”, IEE Conf. Publ. No. 291, 1988, pp. 153-156.

[3] M. Grötzbach, “Line Side Behavior of Uncontrolled Rectifier Bridges with Capacitive dc Smoothing”, Proc. of EPE Conf., 1989, pp. 761 – 764.

[4] M. Grötzbach, T. Strasser, L. Lorenz, “Line Side Harmonics of Three-phase Current Controlled Rectifiers in Continuous and Discontinuous Operation Mode”, Proc. of EPE Conf., 1993, pp. 707-712.

[5] S. Hansen, P. Nielsen, F. Blaabjerg, ”Harmonic Cancellation by Mixing Non-linear Single-phase and Three-phase Loads”, IEEE Trans. on Industry Applications, Vol. 36, No. 1, 2000, pp. 152 - 159.

[6] S. Jeong, J. Choi, “Line Curent Characteristics of the Three-Phase Uncontrolled Rectifiers under Line Voltage Unbalance Conditions”, IEEE Trans. On Power Electronics, Vol. 17, No. 6, 2002, pp. 935 – 945.

[7] S. Hansen, “Harmonic Distortion of Rectifier Topologies for Adjustable Speed Drives“ Ph.D. dissertation, Aalborg University, Institute of Energy Technology, 2000, ISBN 87-89179-37-4.

[8] S. Hansen, P. Nielsen, P. Thøgersen, “Harmonic Distortion and Reduction Techniques of PWM Adjustable Speed Drives – A Cost Benefit Analysis”, Proc. of NORpie Conf., 2000, Aalborg, Denmark, pp. 271-277.

[9] D. E. Rice, “A Detailed Analyze of Six-Pulse Converter Harmonic Current”, IEEE Trans. on Industry Applications, Vol. 30, No. 2, 1994, pp. 294-304.

[10] IEEE Std 519-1992 “IEEE Recommended Practice and Requirement for Harmonic Control in Electrical Power Systems“, IEEE, 1993, ISBN 1-55937-239-7.

[11] N. Mohan, T. M. Undeland, W. P. Robbins, ”Power Electronics”, John Willey & Sons, 1995, ISBN 0-471-30576-6.

[12] M. Sakui, H. Fujita, “An Analytical Method for Calculating Harmonic Currents of a Three-Phase Diode-Bridge Rectifier with dc Filter”, IEEE Trans. on Power Electronics, Vol. 9, No. 6, 1994, pp. 631-637.

[13] Y. Baghzouz, “An Accurate Solution to Line Harmonic Distortion Produced by ac/dc Converters with overlap and dc-ripple”, IEEE Trans. on Industry Applications, Vol. 29, No. 3, 1993, pp. 536 - 540.

[14] M. Grötzbach, M. Bauta, R. Redmann, “Line Side Behavior of Six-Pulse Diode Bridge Rectifiers with AC-side Reactance and Capacitive load”, Proc. of Power Quality Conf., 1995, pp. 525-534.

[15] L. Asiminoaei, S. Hansen, F. Blaabjerg, “Harmonic calculation toolbox in industry application for adjustable speed drive”, Proc. of APEC'04, 2004, Vol. 3, pp. 1628-1634.

[16] S. Hansen, L. Asiminoaei, F. Blaabjerg, ”Simple and Advanced Methods for Calculating Six-Pulse Diode Rectifier Line-Side Harmonics”, Proc. of IAS'03, 2003, Vol. 3, pp. 2056-2062.