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HARMONICS FILTERS AS THE GUARANTEE OF ELECTROMAGNETIC COMPATIBILITY AND HIGH EFFICIENCY OF CONVERTER DRIVE SYSTEMS

Abstract: The article presents the hazards and losses connected with the occurrence of harmonics in the current supplying converters with 6-pulse input. It determines an effective and efficient method for their reduction by means of the proper selection of ElhandHF harmonics filters, which ensure the compatibility of the entire drive system in accordance with IEEE 519 and EN 61000 standards. The filters described are designed, performed and tested in field conditions, and the said works provide the series of types of filters intended for typical drive systems. The said filters enable to maintain the high quality of the mains voltage, they reduce power losses and, at the same time, operating costs. They also increase the reliability and efficiency of converter drive systems. The article also presents the benefits arising from the application of multi-gap cores in the filters, which are performed in an innovative and low-loss ElhandCutCore technology.

Key words: *harmonics filters, electromagnetic compatibility, multi-gap cores*

1. Introduction

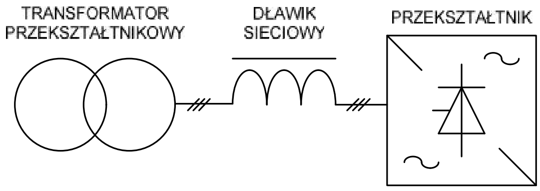
The quality of electricity is a broad aspect which covers many detailed technical problems. The subject of the energy quality is an important issue and its significance is continuously increasing since the costs of poor energy quality are incurred by all of us. The low quality of power supply generates losses in the power engineering, industry and in the event of individual customers. The above is caused by the dynamic development of power electronics and the common use of power converters, frequency converters, UPSs and other non-linear receivers. Drive systems are now more often used as receivers where a frequency converter with 6-pulse input serves as an adjustable power supply source. Currently, this is the simplest and the most common solution which, nevertheless, causes many interferences and interruption in an electromagnetic field. What is most problematic here are the current harmonics (generated through 6-pulse input) because they trigger off most of negative effects in the electrical system. Therefore, while applying this type of solutions, one must pay particular attention to their electromagnetic compatibility in order to avoid unexpected failures, increased electricity charges or the generation of interferences to the mains and other receivers. The study below is aimed at identifying a correct and optimal selection of magnetic elements and increasing the efficiency of the entire drive system.

2. Permissible emission levels of harmonics

The limitations in the harmonics emission level in the point of common coupling are increasingly common among the requirements for converter drive systems. The standards and applicable regulations within this scope refer mostly to the limits for voltage harmonics and for the total harmonic distortion THDu in the point of common coupling (EN 61000-2-2, EN 61000-2-4). Nevertheless, one must note that this is the distorted current consumption from the grid which causes the supply voltage distortion which in turn affects adversely the operation of the entire power system and receivers supplied from this system. Therefore, increased requirements concerning electricity quality and the electromagnetic compatibility of devices contributed to the fact that the requirements of standards are now applied more frequently, which limits the emission level of current harmonics and total harmonic distortion THDi as well as current consumption from the grid (EN 61000-3-2, EN 61000-3-12). Currently, the most stringent requirements within this scope are included in IEEE 519 recommendations applicable in the USA (*Table 1.*) and they will probably be introduced in Poland. Stricter regulations specifying the level of voltage and current distortion in the point of common coupling is a necessity nowadays. Since only in such a manner with the non-linear receivers whose number is growing, it is possible to maintain electricity quality at an appropriate level and to limit unnecessary active power loss which directly affects the energy price and production costs.

3. The meaning of series impedances in supplying 6-pulse systems with power

The consumption of harmonics currents in supplying 6-pulse systems with power (5h, 7h, 11h, 13h, …) is different depending on the short-circuit impedance in the point of common coupling and inductive elements present in the current circuit.



transformator przekształtnikowy - converter transformer
dławik sieciowy - grid impedance coil
przekształtnik – converter

Fig. 1. Diagram of a typical converter system.

The relative impedance of such a system is as follows:

$$Z[\%] \cong \frac{I_N \times (X_{TR} + X_D) \times \sqrt{3}}{U_N} \times 100 \qquad (1)$$

where:
I_N, U_N – nominal current and voltage
X_{TR} – transformer reactance
X_D – impedance coil reactance

The impedance resultant of the entire power supply circuit determines the values of respective current harmonics and total harmonic distortion THDi. In many cases, the power of a power transformer is several times higher than

Table 1. Permissible limits of current harmonics distortion for all devices in the point of common coupling depending on I_{SC} according to IEEE 519

I_{SC}/I_L	**h < 11**	**11 ≤ h < 17**	**17 ≤ h < 23**	**23 ≤ h < 35**	**35 ≤ h**	**THDi**
< 20	4%	2%	1.5%	0.6%	0.3%	**5%**
20 < 50	7%	3.5%	2.5%	1%	0.5%	**8%**
50 < 100	10%	4.5%	4%	1.5%	0.7%	**12%**
100 < 1000	12%	5.5%	5%	2%	1%	**15%**
> 1000	15%	7%	6%	2.5%	1.4%	**20%**
I_{SC} – max. short-circuit current in the point of common coupling; I_L – max. load current in the point of common coupling						

the power of a receiver supplied with power, which means that transformer impedance is for this load proportionally several times lower.

Example: Transformer 1000kVA with relative short-circuit impedance of 6%, for the load of 100kVA will constitute merely 0.6% of impedance. In addition, if e.g. a converter were that load which does not operate at its full power, then the actual effective short-circuit impedance "visible" through the said converter would be even lower and the limitation of harmonics would be negligible (*Table 2*).

As illustrated in the example above, the meaning of the actual circuit impedance is significant and the correct analysis of the contents of harmonics in the converter input current is essential while selecting and thermal dimensioning of magnetic elements working with it. The users of such systems often think that each converter transformer or input impedance coil will solve all the problems connected with the occurrence of harmonics; however, it is not true. A correctly selected converter transformer or input impedance coil will partially limit the impact of the converter exerted onto the grid and other receivers; nevertheless, it is only a necessary minimum. Even the use of 5% impedance will limit total harmonic distortion THDi only to approximately 35%. Using very high impedances is not practised due to a high voltage drop and in consequence the system power drop.

4. The influence of current distortion on the operation of magnetic elements

The flow of distorted currents affects the operation of transformers and impedance coils highly adversely. It is mostly visible in the growth of power losses which exert a direct impact on the thermal work conditions and a service life of such devices. The scale of this hazard is described perfectly in materials [3,4,6] which present the quantitative increase of load losses in transformers depending on the contents of harmonics in the load current:

a) factor of additional losses on the increase of current effective value:

$$F_i^2 = \sum_1^h \left(\frac{I_h}{I_1}\right)^2 = \left(\frac{I_{N_{RMS}}}{I_1}\right)^2 \tag{2}$$

where:
I_h – harmonic current value in raw h, I_1 – effective value of basic harmonic h – harmonic number

b) factor of eddy losses in coiling (K-factor):

$$F_w = \sum_1^h \left(\frac{I_h}{I_1}\right)^2 \times h^2 \tag{3}$$

c) factor of eddy losses in couplings and structural parts:

Table 2. Current harmonic distortions at the input of 6-pulse system depending on the effective impedance of short-circuit (values determined in SIMULINK environment)

Harmonic number	**Percentage value of effective impedance**						
	0.5%	**1%**	**1.5%**	**2%**	**3%**	**4%**	**5%**
5h	78%	60%	51%	46%	39%	35%	32%
7h	58%	36%	28%	23%	17.5%	14.5%	12.5%
11h	18%	13%	11%	9%	7.5%	6.5%	6%
13h	10%	8%	6.5%	6%	5%	4.3%	4%
17h	7.5%	5%	4%	3.6%	3%	2.5%	2.3%
19h	6%	4%	3.3%	3%	2.3%	2%	1.8%
23h	5%	3%	2.6%	2%	1.5%	1.3%	1.1%
25h	2.3%	2%	1.6%	1.3%	1.1%	1%	0.9%
THDi	**100%**	**72%**	**60%**	**55%**	**44%**	**39%**	**35%**

$$F_p = F_k = \sum_{1}^{h} \left(\frac{I_h}{I_1} \right)^2 \times h^{0,8} \tag{4}$$

Total load losses in a transformer P_C, during the flow in the coils of distorted current are as follows:

$$P_C = P_p \times F_i^2 + P_w \times F_w + P_{dk} \times F_k + P_{do} \times F_p \tag{5}$$

where:

P_p – basic losses, P_w – eddy losses in coils, P_{dk} – additional losses in structural parts, P_{do} – additional losses in outflows.

The above relationships may also be applied in the case of impedance coils. Nevertheless, it is necessary to take account of one more extremely important constituent of additional losses – from the fringing flux of air gap P_{Ff} discussed in item 6.

Excessive load current distortion may lead to the increase of additional losses in magnetic elements even several-fold (*Table 3*). It means the higher generation of heat and the temperature increase of their operation and eventually the reduction of a service life or even destruction. Therefore, magnetic elements for distorted currents must be thermally over-dimensioned depending on the current distortion degree or their power rating must be reduced. It is possible to conduct estimate power conversion on the basis of K-factor (*Table 4*), whose contribution is the highest as far as additional losses are concerned. Nevertheless, one must note that this method will not limit basic or additional power losses but it only prevents their effects owing to a larger and more expensive device. Only limiting the current harmonics to an appropriately low level (*Table 1*) will enable to avoid the overdimensioning of magnetic elements and it will improve the efficiency of the entire system.

Table 3. The impact of current distortion on additional losses in magnetic elements

Input circuit	Impedance 1%	Impedance 5%	**Filter HF**
THDi	**72%**	**35%**	**5%**
F_i^2	1.51	1.12	**1.01**
F_w	21.5	5.42	**1.42**
$F_p = F_k$	3.14	1.49	**1.03**

5. Harmonics filters

There are many methods for the elimination and limitation of harmonics in the input current of converters. However, starting with simple series impedance coils and ending with complex active systems, each filtering technique has different costs, power losses and the efficiency of attenuating harmonics. ElhandHF passive filters may certainly be included in the category of devices which are characteristic for an extremely high effectiveness of attenuating harmonics and extremely high efficiency. The said filters have been created on the basis of the integrated connection of series inductivity and parallel resonance branch (*Fig. 2*). An optimal filter structure and the correct adjustment of parameters of its particular parts allows for the effective limitation of harmonics generated by converters irrespectively of the structure and parameters of the grid in the point of common coupling. A parallel filter branch is the appropriate harmonisation of inductivity and capacity of low resultant impedance for a specific harmonic frequency. Whereas, series inductivity improves filtering effectiveness and limits the impact of interferences and hazards occurring on the grid side. Filter attenuation is adjusted so that even with low grid impedance it is not necessary to use additional impedance

Table 4. Power conversion degree depending on K-factor [3]

K-factor (F_w)	K4	K9	K13	K20	K30	K40	K50
Sn x	0.886	0.761	0.692	0.606	0.524	0.469	0.428

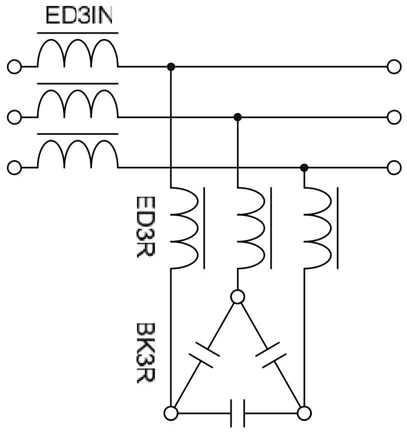


Fig. 2. Circuit diagram of ElhandHF harmonics filter

coils. The filter limits the value of THDi factor at the input of 6-pulse system to the level below 5% with full load. Power losses in the filter do not exceed 1% in relation to the power of the drive system. Such filters outrank other passive filtering techniques not only in terms of very high efficiency but also in terms of maintaining low THDi factor within the comprehensive scope of changes in load as well as with the asymmetry of supply voltage. High efficiency and constant parameters regardless of the load have been achieved owing to the unique structure of multi-gap cores which enabled to create the entire family of ElhandHF high-efficiency harmonic filters.

Fig. 3. ElhandHF input harmonics filter (400kW)

6. Multi-gap cores

The flow of alternating current in the coils of magnetic elements causes the flow of alternating magnetic flux. The main flux part is closed in the magnetic core and the remaining part in the form of fringing fluxes permeates through the coils and other structural elements while generating additional power loss inside them. Determining such losses is a complex aspect and this issue gets even more complicated if we have to do with core discontinuity in the form of a non-magnetic gap. In the areas near the gap, there is a very high dispersion of a magnetic flux (*Fig. 4*), and the dispersion field distribution depends primarily on the size of a gap and the density of the main flux (*Fig. 5*). A resultant air gap in large impedance coils or filters reaches a few or even in some cases several centimetres. It all depends on the required linearity of magnetic specification.

In the event of resonance filters, this parameter is a key parameter since only the unchangeable value of inductivity within the full scope of load current enables obtaining constant resonance frequency, and thus specified attenuation. The inductivity linearity within the broad scope of load current is connected with the necessity of introducing a high resultant of a non-magnetic gap. The above hinders significantly the designing of an optimal impedance coil with limited power losses, limited noise and the intensity of an external magnetic field. Large gaps lead to the increase of power losses in the areas near the gap both in the core and in coils P_{Ff}. Distorted current, at the same time, distorted magnetic flux, escalates harmful phenomena.

In extreme cases, the losses on flux dispersion in the area near the gap may significantly exceed basic losses and lead to the local overheating of the device. The detailed calculation of losses P_{Ff} and the analysis of a

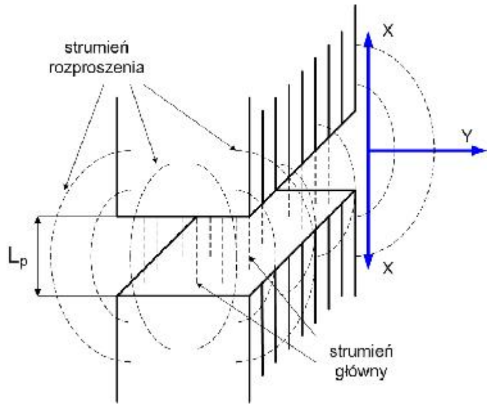
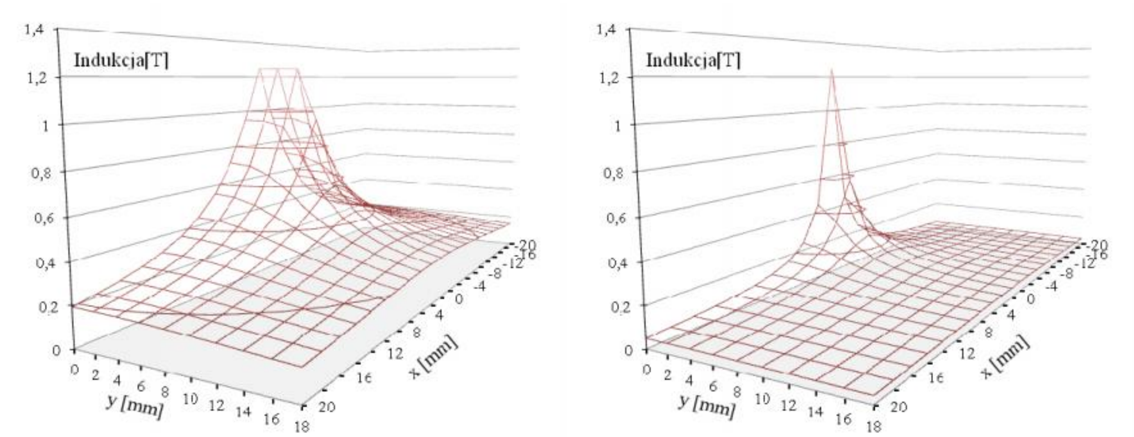


Fig. 4. Main flux and fringing flux in the by-gap area

magnetic field in the core and coils require the application of finite elements methods and it is very time-consuming. Yet, only such an approach towards this aspect allowed to create a manufacturing technology for ElhandCutCore™ multi-gap cores (*Fig. 6.*). In the said cores, through the appropriate arrangement and the precise determination of the respective width of non-magnetic gaps, it is possible to obtain the even distribution of induction and the limitation of inconvenient power losses P_{Ff} to minimum.

7. Testing the effectiveness of attenuating harmonics filters

The authors of this paper have been conducting development and optimisation works for many years within the scope of inductive elements. The effect of the said works is, inter alia, the family of harmonic filters of high-efficiency on the basis of multi-gap cores. One of the key issues while selecting and designing inductive elements working together with converters is the correct determination of the input current shape since, as it has been demonstrated, it has a crucial meaning for thermal work conditions and the efficiency of a magnetic element. Therefore, the object of tests was the determination of the harmonics emission level in the converter system with 6-pulse input (160kW, 400V, 50Hz) for the various effective impedance of the input circuit:
a) without grid impedance coil (effective grid impedance in the point of common coupling for the tested converter was approx. 1%),
b) with grid impedance coil of 4% (resultant impedance with consideration of grid impedance was 5%),
c) with harmonics filter of ElhandHF type.
The tests and the analysis of the contents of harmonics in the course of converter input current for each of the aforementioned cases (*Fig. 8*) demonstrated that the measurement results obtained are correspondent with the values of harmonics determined by computer simulation (*Table 2*)



indukcja – inductivity

Fig. 5. Density of a fringing flux in the area near the gap for the various width of non-magnetic gap: a) gap 10 [mm], b) gap 2.5 [mm]

Fig. 6. Multi-gap core in ElhandCutCore^{TM} technology

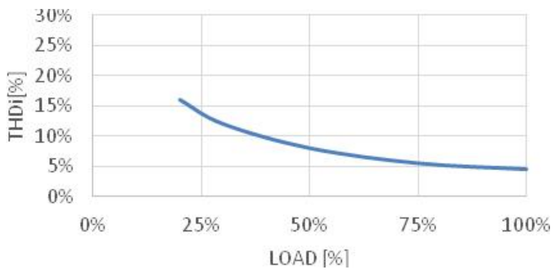


Fig. 7. THDi of input current for160kW filter in the loading function

8. Summary

The negative effects and costs of the occurrence of higher harmonics in the converter input current are an obvious problem encountered by the users of converter drive systems. The necessity of overdimensioning the magnetic elements working with a converter, additional power losses, interferences and increasing requirements concerning the harmonics emission in the point of common coupling force to search for the solutions which not only will eliminate the effects of harmonics but also will limit them effectively in their occurrence point. A decision on the selection of an appropriate solution ought to be preceded by a detailed analysis of the entire drive system both in terms of electromagnetic compatibility and efficiency of all the devices. One must not be guided only by a criterion of a price since it frequently leads to the generation of additional active power losses, and apparent savings will have to be returned, even exceeding their amount, to a power plant in the form of active energy fees. Therefore, rational electricity management means nowadays the selection of devices of top efficiency since nothing convinces a user better than total and actual costs which will be incurred by such a user in the event of converter drive system.

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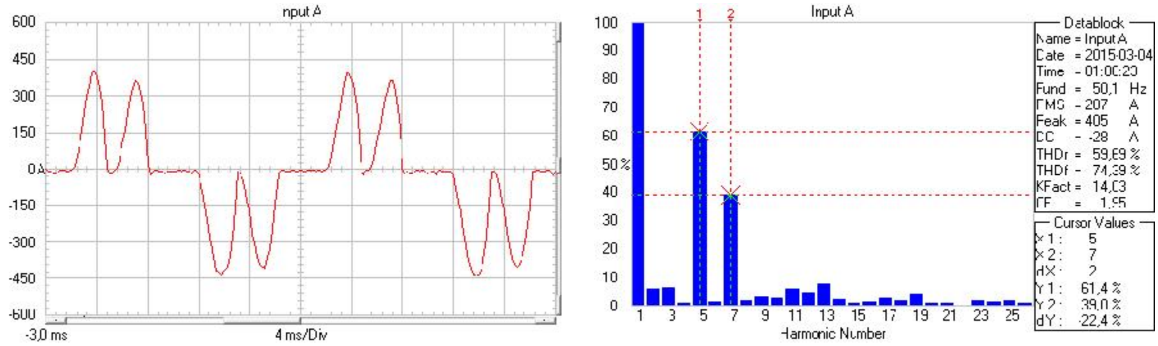

Fig. 8.a. Oscillograph records of the input current in the converter at 1% effective impedance

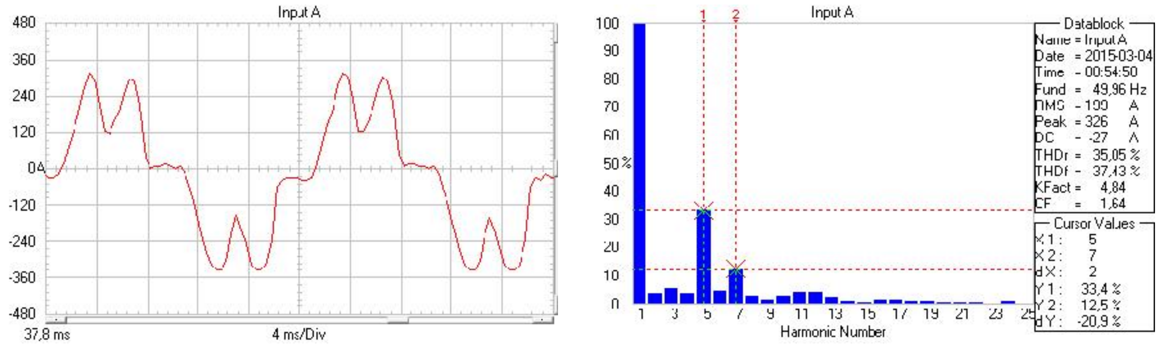

Fig. 8.b. Oscillograph records of the input current in the converter at 5% effective impedance

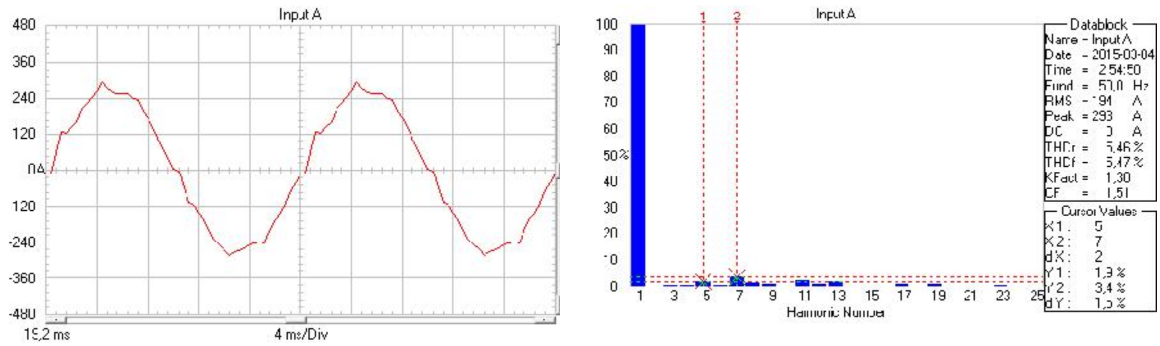

Fig. 8.c. Oscillograph records of the input current in the converter with the harmonics filter

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