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The effect of harmonic filters on improvement of electrical energy parameters at point of common coupling

Summary. *Nowadays, the most common solution in the drive system are converters with a 6-pulse input. Dependency of the 6-pulse converter input current on parameters of the point of common coupling and serial reactances have been shown. The work also depicts negative impact of current wave deformations on magnetic components. The effect of harmonic filters on parameters and operation of the converter drive system have been presented.*

Keywords: harmonic filters, harmonics in drive systems, converter drive systems.

Introduction

The world market of converter drive systems is one of the most dynamically developing markets. Today, over half of the global electric energy used by the industry is consumed by drive systems. Currently, more and more often, the decisive factor relating to the purchase of such devices is a thorough economic analysis, covering real return on investment and the analysis of the whole system influence onto the supplying grid and other receivers [1]. The solutions of drive systems used nowadays are not free from faults and that is why they are being strongly developed. The knowledge relating to electromagnetic, mechanical, thermal, acoustic and other phenomena occurring therein is deepened. However, the everlasting conflict, but at the same time, the need to achieve compromise between the energy saving and material saving of a given solution still makes up the key challenge. The times when the reserve capacity was a standard are long gone. That is why, today the European Commission regularly prepares and introduces specific provisions and requirements for particular groups of devices (for instance EN 50598-2 or UE Regulation No. 548/2014 - EcoDesign Directive). These provisions determine, most of all, the minimal requirements in the scope of the efficiency of particular machines and devices. This is to protect against too “economical” designing of devices and to improve the energy efficiency of the system and the industry.

The effects of the point of common coupling parameters on the distortion of converter input current

Point of common coupling *(PCC)* may be treated as the source of sinusoidal voltage or the electrical grid with specified internal impedance of inductive characteristics. The indicator which directly binds the dependence of the input current of coupled converter with the parameters at the point of common coupling is the short circuit ratio *SCR*,

$$SCR = \frac{I_{SC}}{I_L} \tag{1}$$

where: I_{SC} – short circuit current at the point of common coupling, I_L – load current at the point of common coupling.

Short circuit ratio defines the stiffness of the point of common coupling in relation to supplied receivers. Generally, the greater the relation of the short circuit power at the point of common coupling to the power of the supplied receiver the stiffer the grid is, and the current supplied from the grid by the converter is more distorted, with higher effective value. To limit THD_I distortion and effective value of the converter input current, the short circuit current at point of common coupling should be limited. The interference in the short circuit power at the point of a common coupling is costly and it basically is possible only at the stage of the grid designing. In practice, the most common and the easiest manner to limit the distortion of the current waveform is the increase of the impedance of the short circuit loop of the drive system. It may be carried out, in a certain scope, by adding additional serial reactances on the input side of the converter (for instance: rectifier transformer with appropriate short circuit voltage or line reactor of a defined inductance). Influence of additional reactances in the current circuit of converter supply was presented in Figure 1.

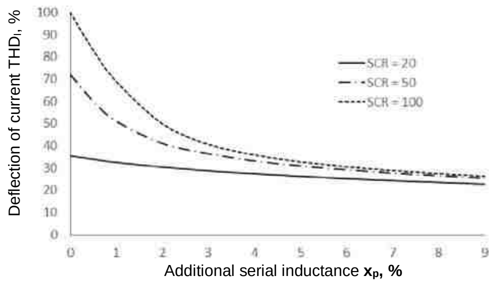

Figure 1. Influence of additional serial reactance on the deflection of the converter input current [1].

Figure 1 presents the dependency of converter input current distortion of the rating power of 250kW and the short circuit power at point of common coupling and additional serial reactances. This dependency, however, has a general nature. Three cases of supplying transformers were considered; of short circuit voltage of U_X=6%, differing with rated power: S_{TR} = 315kVA *(SCR* = 20), S_{TR} = 1000kVA *(SCR* = 50), S_{TR} = 2500kVA *(SCR* = 100). The carried out analysis indicates that the converter transformer and the serial inductances limit, to a certain degree, the influence of the converter on the supplying grid and other receivers, but it is only the necessary minimum. Even the application of 5-6% additional serial reactance shall limit the total deflection ratio *THDi* only to about 30-35%. However, the application of greater serial impedances is not used in practice due to large drops of voltage, and thus, the decrease of the drive system power [2]. More effective solution to limit the converter current harmonics is the use of passive harmonic filters. The difference in the converter system input current without filter and with filer was presented in Table 1.

Table 1. Dependency of the effective values of 6-pulse 250kW converter current and *SCR* parameter at point of common coupling.

PCC parameters		*THD*i, %	I_{rms}, A	$I_{h\,(RMS)}$, A				
SCR	Filter			1 h	5h	7h	11 h	13h
20	No	35.4	375	353	116.6	34.7	22.8	11.6
	Yes	**4.9**	**354**	**353**	**8.9**	**12.3**	**7.0**	**2.9**
50	No	74.2	459	369	232.1	138.9	25.6	26.3
	Yes	**5.6**	**356**	**355**	**10.4**	**14.1**	**7.7**	**3.1**
100	No	99.9	541	383	295.0	222.7	82.9	37.1
	Yes	**5.8**	**357**	**356**	**10.9**	**14.7**	**7.9**	**3.2**

In the system with the passive harmonics filter, irrespective of the short circuit parameters of point of common coupling, THD_I in the scope of 5-6% was achieved, and thus, less effective value of converter input current.

The effects of current waveform distortion on the work of passive magnetic elements

The flow of the current distorted by electromagnetic elements influences adversely their work, causing the quantitative increase of power losses. Depending on the harmonics content in the current spectrum, it is possible to calculate approximately these losses in passive magnetic elements determining the ratios of stray losses and total losses [3, 4, 5]:

a) ratio of stray losses and increase of current effective value:

$$F_i^2 = \sum_{h=1}^{n}\left(\frac{I_h}{I_1}\right)^2 = \left(\frac{I_{N_{RMS}}}{I_1}\right)^2 \tag{2}$$

where: I_h – value of current of harmonic *h* grade, I_1 – effective value of basic harmonic, *h* – harmonic number.

b) ratio of eddy current losses in windings (K-factor):

$$F_w = \sum_{h=1}^{n}\left(\frac{I_h}{I_1}\right)^2 h^2 \tag{3}$$

c) ratio of eddy current losses in connections and construction parts (stray losses)

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

Due to the flow in the winding of distorted current, the total load losses in P_C transformer amount to:

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

where: P_p - basic losses, P_w - eddy current losses in windings, P_{dk} - stray losses in construction parts, P_{do} - stray losses in outflows.

In case of reactors, total losses P_c should be complemented by a component of stray losses P_{FF} (fringing flux), which represent losses in winding associated with leakage flux around air gaps. The value of this component may be minimized by the application of multi-spaces cores or using magnetic material of very low permeability μ_r into the air space. Whereas, basic losses in the reactor core should be increased by losses P_G in the space, which are the dependent of [6]:

$$P_G = K_g \frac{n_g l_g w}{\rho} f B^2 \tag{6}$$

where: K_g – empirical factor dependent upon core construction, n_g – number of air gaps, l_g – length of gaps, *w* – sheet width, *ρ* – resistivity of core material, *f* – frequency, *B* – induction amplitude.

Load current distortion causes the stray losses in magnetic elements may increase even several times (Tab. 2). As a result of increased heat production and direct increase of temperature, the life-span of devices drops and causes their damage in extreme cases. As a consequence, the magnetic elements for cooperation with the deflected currents must be thermally oversized, depending on the degree of current distortion (larger cross-section of core, coil wire or tape, application of transpositioned winding, etc.) or their power rating must be limited.

Table 2. Influence of current distortion on stray losses in magnetic elements on the example of 250kW converter.

	SCR= 100	*SCR* = 50	*SCR* = 20	**Passive filter**
THD_I	99.7%	74.2%	35.4%	**5%**
F_i^2	1.99	1.55	1.12	**1.01**
F_w (K-factor)	43.9	20.8	5.53	**1.19**
$F_p = F_k$	5.23	3.21	1.49	**1.01**

Estimated power over-rating may be carried out based on the K-factor (Fig. 2), which is expressed as the sum of subsequent squares of effective value and harmonic row number. However, it should be underlined, that in this manner we shall not limit basic or stray losses of power. We can only counter the effects thereof at the expense of bigger and more expensive device. Only the limitation of higher harmonics in the current spectrum to appropriately low level will allow to limit the stray losses. This, in turn, improves the efficiency of the entire system.

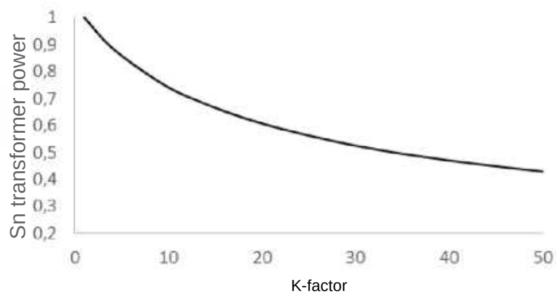

Figure 2. The ratio of transformer power over-sizing depending upon K-factor

Methods of elimination and admissible levels of current harmonic emissions

There are many methods of elimination and limitation of harmonics in the converters input current. Starting from simple AC and DC reactors, multi-pulse systems, passive filters and ending with complicated active systems. Each of the filtration method is characterised by different efficiency of harmonic attenuation, different losses, different purchase costs and exploitation (Table 3).

AC and DC reactors are the cheapest method of limiting harmonics in supply current and, therefore, also the effective value of that current; unfortunately, today it is an insufficient minimum, which does not fulfil the required standards.

Table 3. Comparison of efficiency and relative costs of different methods of elimination of current harmonics

Method of limiting of current harmonic	Current distortion (*THD*i)	Relative cost
Systems without filtration	60 – 120 %	1
2% AC or DC reactors	30 – 60 %	2
4% AC or DC reactors	25 – 45 %	3
12-pulse systems	10 – 15 %	4
Passive filters	**5 – 8 %**	**4**
18-pulse systems	4 – 6 %	5
Active filters	3 – 5 %	5

Due to phase shift between secondary windings of transformer, it is possible to eliminate each harmonic in multi-pulse circuits (in 12-pulse system we eliminate the 5th and 7th harmonic, whereas in 18-pulse system additionally 11th and 13th). The main defect of multi-pulse circuits is their sensitivity to load asymmetry and unbalance or distortion of supply voltage. Then, it is not possible to efficiently limit the harmonics (the 5th, 7th as well as 11th and 13th). It causes the current THD_I increases the above assumed values, which in many cases may lead to non-fulfilment of the assumed parameters.

Both passive and active filters are partially resistant to supply voltage asymmetry and their attenuation properties allow to fulfil stringent standards for voltage and current in the point of common coupling. Active filters advantage is maintaining of low level of current *THD*i in full load, but it is directly reflected in the purchase price of such device.

Today, no one needs to be convinced that limitations or elimination of harmonics is a necessity. There is still, however, the doubt what method should be chosen and what standards should be fulfilled to avoid unnecessary problems and costs. Current norms and regulations in the scope of harmonics emissions relate to, most of all, harmonics voltage at the point of common coupling (EN 50160, EN 61000-2-2, EN 61000-2-4), and, more rarely in current (EN 61000-3-2, EN 61000-3-12) [7]. However, it should be remembered that voltage deflection is caused by harmonics in the current input collected by non-linear receivers. That is why, the requirements with reference to the limitations of the levels of harmonic emissions, relating both to current and to voltage in the point of common coupling, in accordance with IEEE 519-2014 standard are more and more frequent [8]. It is the standard including in its scope all grids, levels of voltage and current in the point of common coupling (Tab. 4, Tab. 5). It also differentiates the requirement of admissible THD_I of current and each harmonic depending on the grid stiffness and installed power at point of common coupling.

Table 4. Admissible limits of current harmonic distortion for all devices at the point of common coupling depending on I_{SC}/I_L according to IEEE 519-2014

I_{SC}/I_L	h < 11	11 ≤ h <17	17 ≤ h < 23	23 < h < 35	35 < 50	*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%

Table 5. Admissible limits of voltage harmonic at the point of common coupling according to IEEE 519-2014

Voltage in PCC point	Individual harmonic	THD_U
U ≤ 1kV	5.0%	8.0%
1kV < U ≤ 69kV	3.0%	5.0%
69kV < U ≤ 161kV	1.5%	2.5%
161kV < U	1.0%	1.5%

Influence of harmonics filters on the efficiency and reliability of drive system

The efficiency of electric device is the relation of the power given on the output by that device (P_{OUT}) to the power on the input of the device (P_{IN}). It allows to define total losses of machine power. The situation is similar in case of defining of the efficiency and losses of converter drive systems. However, here the issue becomes more complex, as these circuits are usually made of several machines and devices, which additionally are mutually interdependent. For example, the efficiency of the circuit in Figure 5 may be determined in the following manner:

$$\eta_{\substack{Drive\\System}} = \frac{P_{OUT}}{P_{IN}} = \frac{P_{OUT}}{P_{OUT}+\Delta P_{\substack{Total\\Losses}}} \tag{7}$$

where: $\Delta P_{\text{Total Losses}}$ - sum of component losses of the drive system.

It equals to the product of the efficiency of each component of drive systems, starting from point of common coupling (PCC):

$$\eta_{\substack{Drive\\System}} = \eta_{Tr}\cdot\eta_{HF}\cdot\eta_{FC}\cdot\eta_{M} \tag{8}$$

In practice, the issue of the efficiency of converter drive system is very often recognised erroneously, without taking into consideration the influence of the converter

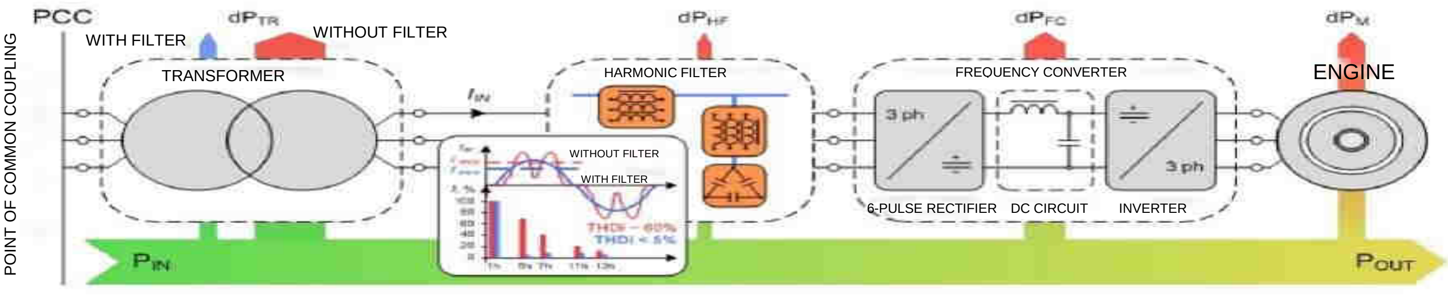

Figure 3. Power flow in a typical converter drive system in the circuit with harmonic filter and without harmonic filter [9].

into transformer, grid and other receivers. It lowers the supply quality and power effectiveness of the entire system. To avoid it, each converter should be separated and equipped with the device limiting the harmonic emission to input grid.

Due to high attenuation and efficiency, passive harmonics filters make up optimal alternative (filtration efficiency compared to the costs of application) when compared to the remaining methods of harmonic elimination in input current of converter circuits (Tab. 3). The filtration efficiency of passive harmonic filters is similar to the 18-pulse circuits and the attenuation dependency on the load level and input voltage unbalance is smaller than in the multi-pulse circuits. Current passive filters are not only the combination of reactors and condensers adjusted to single harmonics. More and more often, they are advanced combination of a set of reactors and condensers to attenuate a defined harmonic scope. Compact reactor solutions, performed on a common ferromagnetic core become a standard (Figure 4) [9].

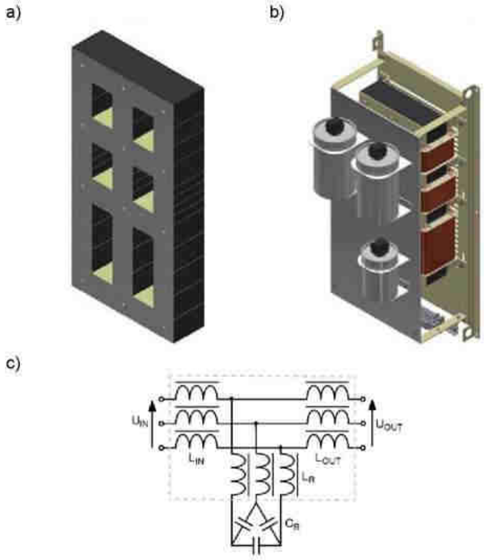

Figure 4. EF3H harmonics filter of 55kW power: a) construction of multi-reactor core with mutual yokes; b) compact structure of harmonic filter; c) schematic diagram of the filter [9]

Structure of mutual magnetic core (mutual yokes) in multi-reactor filter contributes to limiting of dimensions and weight of the device. Inductance of particular reactors allows for shaping the characteristics of filter attenuation appropriately (Figure 5).

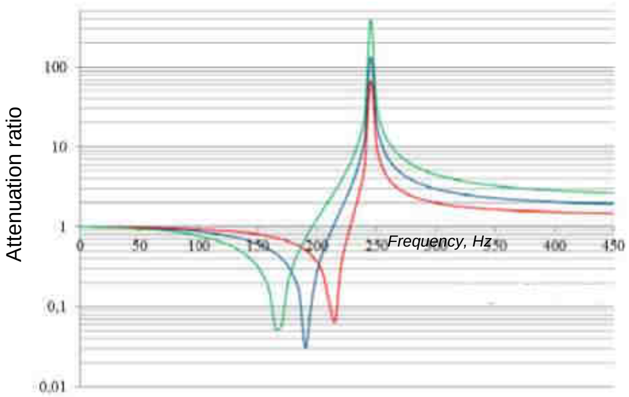

Figure 5. Characteristics of multi-reactor filter attenuation [9].

Parallel reactor, together with the condenser's battery makes up resonance trap for a particular harmonic. Series reactors (input and output) influence the attenuation band width and preliminary limit of harmonic of higher grade. Reactors inductance and capacity of condensers are adjusted so that the filter could achieve proper attenuation in the broad scope of load and proper flow of current in each reactor (Figure 6).

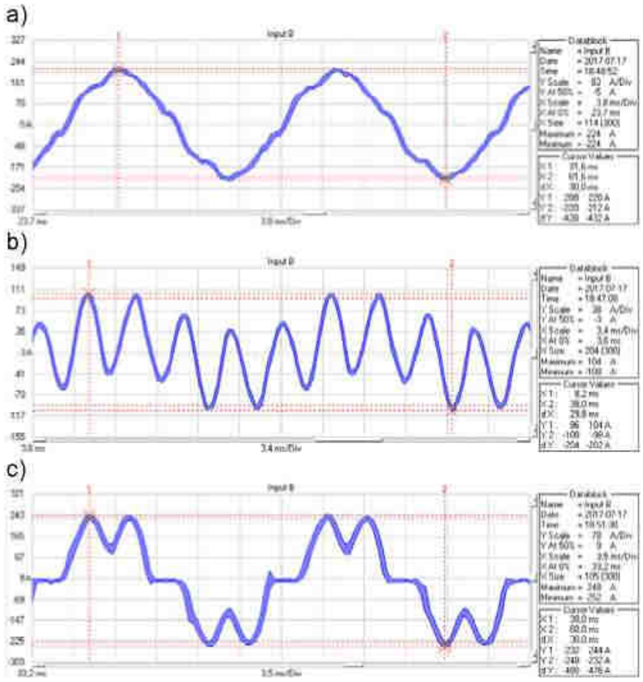

Figure 6. Measurement of current flow in EF3H three-reactor harmonic filter of 110kW power: a) in L_{IN}, input reactor, b) in L_R, resonance reactor, c) in L_{OUT} output reactor [9].

Also, the capacity current intake with lack of load or with insignificant loads makes up a crucial parameter. The structure and optimisation of multi-reactor filters allows to decrease the capacity current even below I_C < 15%I_N of rated current, which is especially crucial in case of motor power, occurring mainly on ships or oil fields. Smaller capacities in the parallel circuit of the filter cause the necessity to apply greater parallel inductance to maintain the resonance condition and greater input inductance to improve the attenuation characteristics of the whole filter. Greater inductances mean greater weight and losses, and, by the same, lesser efficiency of the filter. In case of the multi-reactor filters on a common multi-space core, this effect is not that visible.

Based on typical powers of converter systems, corresponding families of harmonics filters are created, which fulfil the attenuation requirements pursuant to the standard IEEE 519-2014, irrespective the parameters of the point of common coupling. Figure 7 presents the results of measurements of harmonic contents in input current of 55kW converter in the circuit without filter and in the circuit with multi-reactor harmonic filter EF3H-55kW 380-415V±10% T40F. Application of harmonic filter in the system of pumping station supply allowed to decrease THD_I in the current from the level of 40% to the level below 4.5%, which, by the same, eliminated adverse influence of the distorted current onto the remaining receivers in the grid.

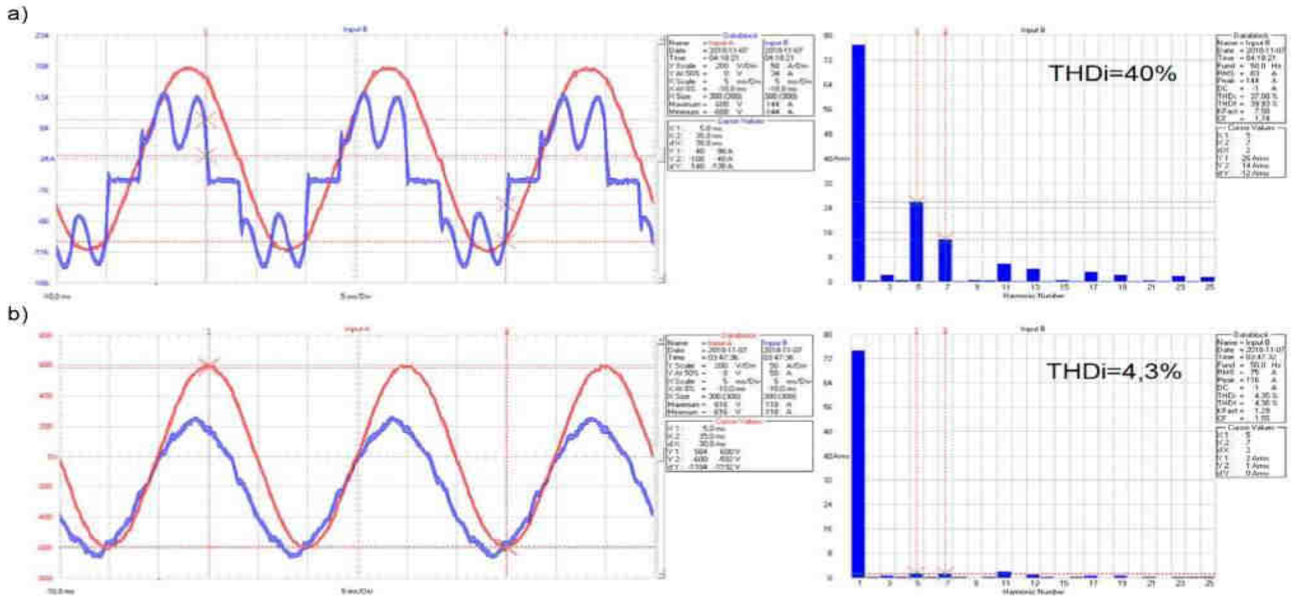

Figure 7. Results of measurement of 55kW converter input current harmonics; a) in the circuit without harmonics filters; b) in the circuit with three-reactor filter on common yokes EF3H-55kW 380-415V±10% T40F [9]

Summary

The cost of converter drive system is a relatively insignificant outlay of expenditures spent by the user for its work during the entire period of exploitation. It is thus worth to have a closer look at the efficiency of the whole system, its influences on the grid and other receivers. Currently, a set of normative solutions which help to maintain the quality of electric energy in the point of common coupling may be found. Converter transformers or series reactors do not solve all the problems and are not in the position to limit the harmonic emission of the current to appropriately low level. Proper analysis of harmonic contents in the converter input current has a particular significance in the choice and thermal balancing of the magnetic elements cooperating therewith. Oversized transformers are waste of energy; it is more reasonable to reduce harmonics than to counter their effects. Increasing awareness of the customers and the demand for the harmonics reduction devices cause that passive harmonic filters are still heavily developed and optimised, which increases their competitiveness. Application of harmonic filters not only contributes to lowering of electric energy costs, but also, in a significant manner, improves the efficiency and reliability of converter drive system.

The article was written as part of the RPO (Regional Program) WSL 2014-2020: "Nowoczesne, energooszczedne układy przetwarzania energii elektrycznej wolne od harmonicznych generowanych przez przekształtniki mocy" (Modern, energy saving systems of electric energy converting free from harmonics generated by power converters) - WND-RPSL.01.02.00-24-0548/17.

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