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HARMONIC FILTERS IN CONVERTER DRIVE SYSTEMS

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Summary: The world market of converter drive systems is one of the most dynamically developing markets nowadays. Today, over half of the globally used electric energy is consumed by drive systems. A thorough economic analysis as well as the real return on investment are increasingly becoming a decisive factor for the purchase of those devices. The objective of this article is to make users of converter drive systems aware of the significant influence the harmonic filters have on the efficiency of the entire system. Dependency of the converter input current on parameters of the point of common coupling and serial reactances have been shown. The work also presents negative impact of current wave deformations on magnetic components. The impact of harmonic filters on parameters and operation of the converter drive system have been presented.

Key words: harmonic filters, harmonics in drive systems, converter drive systems.

1. INTRODUCTION

The necessity of the rotational speed adjustment and soft starting of electric motors has existed practically from the beginning of their origin, i.e. for over 150 years. Over this period, both motors and different methods of its speed adjustment developed tremendously. Normalization and parametrization of solutions were introduced and this changed the attitude towards the design and optimisation of electric machines. Most of all, numeric methods, sudden development of computer hardware and software, as well as significant progress in the area of active and insulation material contributed to that revolution. Adjustment of rotational speed through resistors and regulating reactors or Leonard systems was replaced by the development of semiconductors and modern converter systems. Modern drive systems are not completely free of faults, they are still 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 energy saving and material saving of a given solution still makes up the biggest challenge. The times when reserve capacity was a standard are long gone. That is why, today the European Commission regularly prepares and introduces specific regulations and requirements for particular groups of devices (for instance EN 50598-2 or UE Regulation No. 548/2014 - EcoDesign Directive). These regulations 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.

2. DEPENDENCE OF THE CONVERTER INPUT CURRENT ON PARAMETERS OF THE POINT OF COMMON COUPLING

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.

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

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

Ratio of short circuit is also denominated as R_{SC}; it determines the stiffness of point of common coupling in relation to the 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 converted, with higher effective value. Figure 1 presents this dependency in the grid with the converter of power rating of 250kW. 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 of point of common coupling is costly and, basically, it is possible only at the stage of the grid designing. In practise, the most common and the easiest manner to limit (to a certain level) the distortion of the current course is to increase the impedance of the short circuit loop of the drive system by applying of additional serial reactances on the input

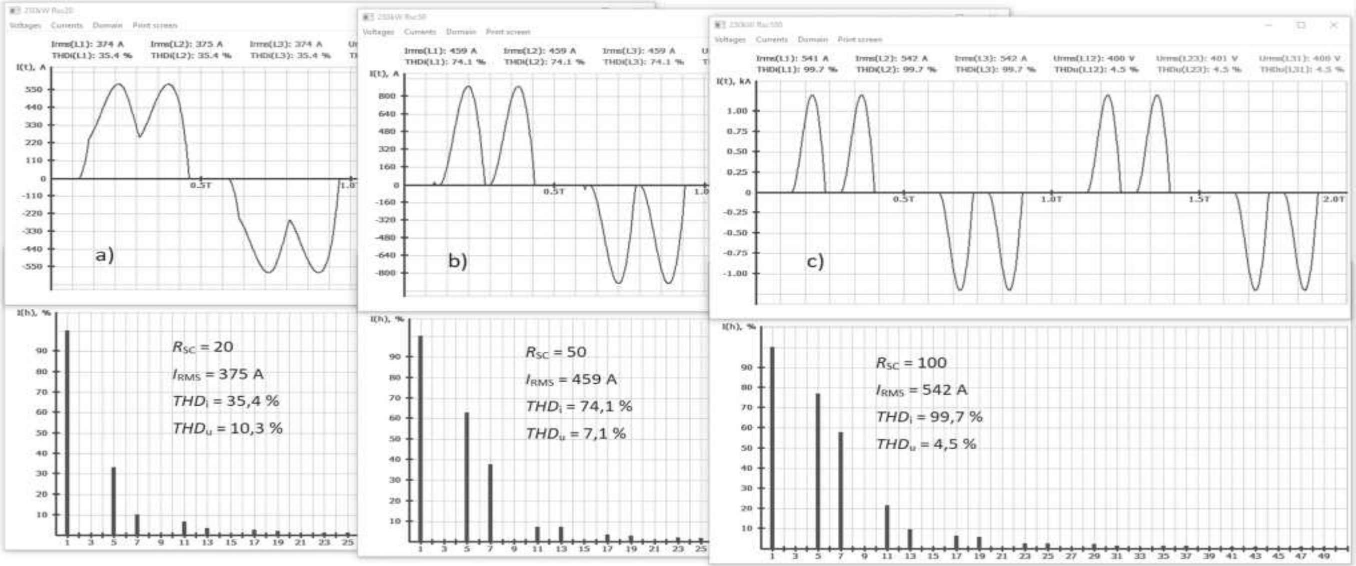

Figure 1. Time course and input current spectrum of 250kW 6-pulse converter in case of different short circuit powers at the point of common coupling; a) S_{TR}=315kVA, u_X=6%; b) S_{TR}=1000kVA, u_X=6%; c) S_{TR}=2500kVA, u_X=6%

side (for instance: rectifier transformer with appropriate short circuit voltage or line reactor of determined inductance, Figure 2).

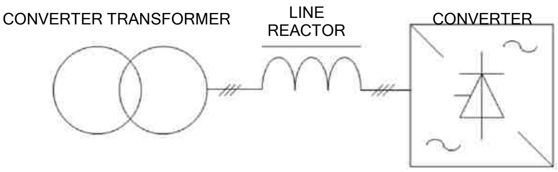

Figure 2. Converter system with additional serial reactances [1]

Relative impedance of such system equals to:

$$z \cong \frac{I_N \times (X_{TR} + X_D) \times \sqrt{3}}{U_N} \times 100\% \tag{2}$$

where:

I_N, U_N – current and voltage rating,

X_{TR}, X_D– reactance of transformer, reactor.

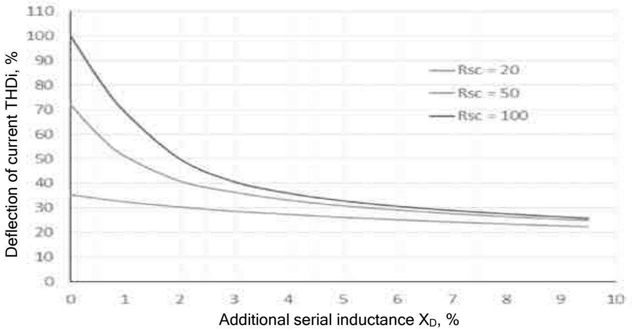

Figure 3. Influence of additional serial reactance on the distortion of the converter input current

Significance of the serial impedance of the circuit is tremendous. Influence of additional reactances in the current circuit of converter supply was presented in Figure 3. Properly chosen rectifier transformer and serial reactors 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 THD_i total distortion ratio only to about 35%. Application of greater serial impedances is not used in practice due to large drops of voltage and, at the same, decrease of the drive system power [1].

3. INFLUENCE OF THE DISTORTION OF THE CONVERTER INPUT CURRENT COURSE ON THE WORK OF MAGNETIC ELEMENTS

Distortion of converter input current influences disadvantageously the work of all magnetic elements which supply it and of other elements supplied by the same grid. The quantitative increase of power losses in transformers and reactors depending upon harmonic contents in the load current may be calculated by denominating the ratio of stray losses and total losses. [2, 3, 4]:

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

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

where:

I_h - value of current of harmonic of grade h,
I_1 - effective value of basic harmonic,
h - number of harmonics.

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

$$F_w = \sum_{h=1}^{n} \left(\frac{I_h}{I_1}\right)^2 \times h^2 \qquad (4)$$

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

$$F_p = F_k = \sum_{h=1}^{n} \left(\frac{I_h}{I_1}\right)^2 \times h^{0,8} \qquad (5)$$

Total load losses in P_C transformer, with the flow in the winding of deflected current amount to:

$$P_C = P_p \times F_i^2 + P_w \times F_w + P_{dk} \times F_k + P_{do} \times F_p \qquad (6)$$

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 completed with one, very important component of stray losses P_{FF} (fringing flux), which represents losses associated with leakage flux around non-magnetic gaps in reactor core. The value of this component may be minimized by the application of multi-gaps cores or introducing magnetic material of very low permeability μ_r into the space.

Load current distortion causes the stray losses in magnetic elements may increase even several times (Tab. 1).

Table 1. Influence of current distortion on stray losses in magnetic elements

	Rsc 100	Rsc 50	Rsc 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**

In consequence, increased losses mean increased heat production and increase in working temperature of devices, and as a result thereof, decrease of their life duration or even their destruction. As a result of the above, to cooperate with deflected currents, the magnetic elements 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. Estimated oversizing of power may be carried out based on the K-factor ratio (Figure 4), which, however, has the largest share with reference to stray losses. It should be remembered that in this manner we do 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 allows to limit the stray losses. This, in turn, improves the efficiency of the entire system.

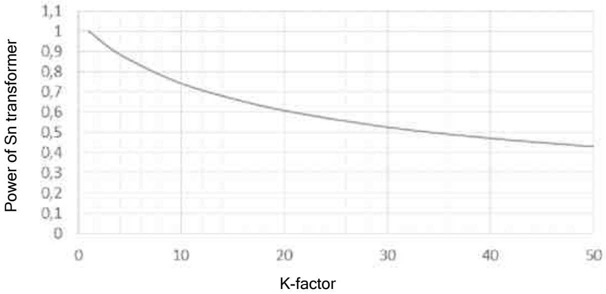

Figure 4. The degree of transformer power oversizing depending upon K-factor

4. METHODS OF ELIMINATION AND ADMISSIBLE LEVELS OF CURRENT HARMONICS 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 characterized by different efficiency of harmonics attenuation, different losses, different purchase prices and different costs of operation (Table 2).

Table 2. Comparison of efficiency and relative costs of different methods of elimination of current harmonics

Method of limiting of current harmonics	Current deflections (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

AC and DC reactors are the cheapest method of limiting the effective value of supply current and certain harmonics reduction in supply current (depending on the reactor reactance) – unfortunately, today it is the insufficient minimum as it does not fully observe the standards in force.

In multi-pulse circuits, due to phase shift between secondary windings of the transformer (two secondary windings in case of 12-pulse circuit, three secondary windings in 18-pulse circuit) and the application of appropriate number of rectifiers, 5th and 7th harmonics are eliminated (in 12-pulse circuit) and additionally 11th and 13th (in 18-pulse circuit). 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 limit harmonics efficiently (5th, 7th as well as 11th and 13th). It causes the current THD_i to increase above the assumed values, which in many cases, may lead to non-fulfilment of assumed parameters.

Both passive and active filters are partially resistant to supply voltage asymmetry and their attenuation properties allow to fulfil

Table 3. Permissible limits of current harmonics deflections 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	THD_i
< 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 4. Admissible limits of voltage harmonic at the point of common coupling according to IEEE 519-2014

Voltage at PCC point	Individual harmonics	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%

the restrictive standards for voltage and current at the point of common coupling. Active filter 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. However, there is still 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) [5]. 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 [6]. It is the standard including in its scope all the grids, levels of voltage and current in the point of common coupling (Tab. 3, Tab. 4). Application of admissible limits of harmonics deflections of current and voltage, already at the early stage of designing of the systems of power supply and non-linear receivers allows for stable and predictable operation of the system during the whole exploitation period.

5. HARMONICS FILTERS - EFFICIENCY AND RELIABILITY OF THE 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 taken on the input (P_{IN}). In this manner, the total losses of the device power may be determined. The situation is similar in case of defining of the efficiency and losses of converter drive system. However, in this case, 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:

$$\eta_{\substack{Drive\\System}} = \frac{P_{Out}}{P_{In}} = \frac{P_{Out}}{P_{Out} + dP_{\substack{Total\\Losses}}} \qquad (7)$$

where:

$$dP_{\substack{Total\\Losses}} = dP_{Tr} + dP_{HF} + dP_{FC} + dP_M \qquad (8)$$

or in the form of efficiency:

$$\eta_{\substack{Drive\\System}} = \eta_{Tr} \times \eta_{HF} \times \eta_{FC} \times \eta_M \qquad (9)$$

Total efficiency of the drive system is the product of the efficiency of each of its elements, starting from the point of common coupling (PCC) or billing point. 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 into transformer, grid and other receivers. It lowers the supply quality and power effectiveness of the whole system. To avoid it, each converter should be separated and equipped with the device limiting the harmonics emission to input grid.

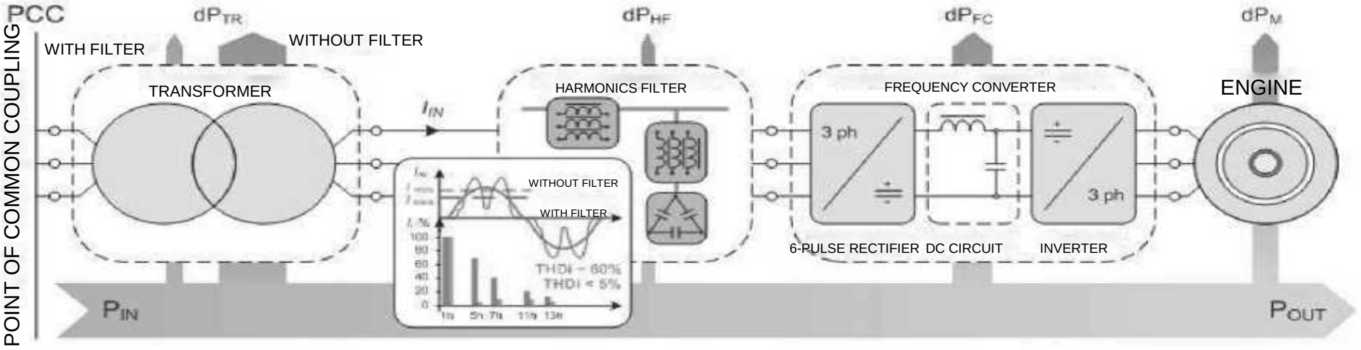

Figure 5. Power flow in a typical converter drive system in the circuit with harmonic filter and without harmonic filter [7].

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. 2). 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 6) [7].

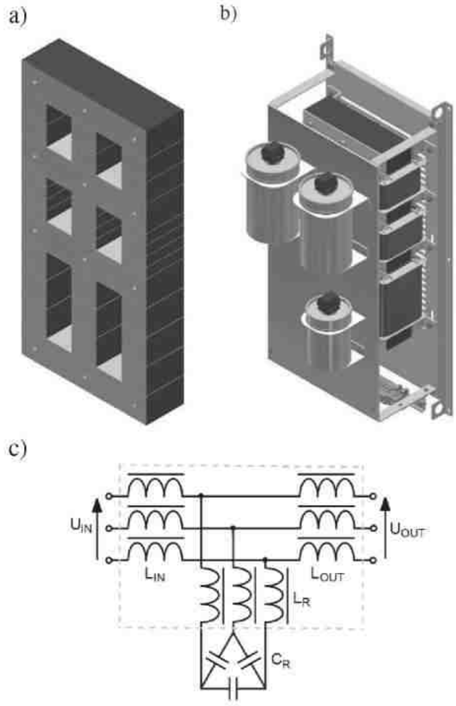

Figure 6. EF3H 55kW harmonics filter: a) structure of multi-reactor core with mutual yokes; b) compact structure of harmonic filter; c) schematic diagram of the filter [7]

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 7). Parallel reactor, together with the condenser's battery makes up resonance trap for a determined harmonic. Series reactors (input and output) influence the attenuation band width and preliminary limiting of harmonics of higher grade. Reactors inductance and capacity of condensers are selected so that the filter could achieve proper attenuation in the broad scope of load. 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.

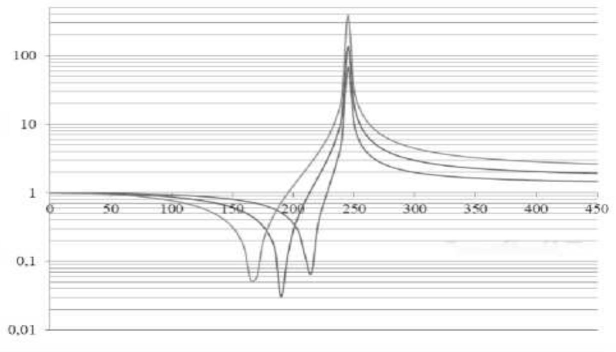

Figure 7. Exemplary characteristics of multi-reactor attenuation.

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 8 presents the results of measurements of harmonics contents in input current of 55kW converter in the circuit without filter and in the circuit with multi-reactor harmonics filter EF3H-55kW 380-415V±10% T40F. Application of harmonics 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%, thus eliminating the adverse influence of the distorted current onto the remaining receivers in the grid.

6. SUMMARY

The influence of the converter systems on the grid is a very broad, still current and increasing problem. It forces the legislators to introduce normative solutions which help to maintain the quality of electric energy at the point of common coupling. Converter transformers or series reactors do not solve all the problems and are not in the position to limit the harmonics emission of the current to appropriately low level. Proper analysis of harmonics contents in the converter input current has a particular significance in the selection and thermal balancing of the magnetic elements cooperating therewith. Oversized transformers are a waste of energy; it is more reasonable to reduce the harmonics than to counter their effects. Increasing awareness of the customers and the demand for the harmonics reduction devices cause that the passive harmonics filters are still heavily developed and optimised, which increases their competitiveness. Application of the harmonics filters not only contributes to lowering of electric energy costs, but also, improves the efficiency and reliability of converter drive system, even in a significant manner.

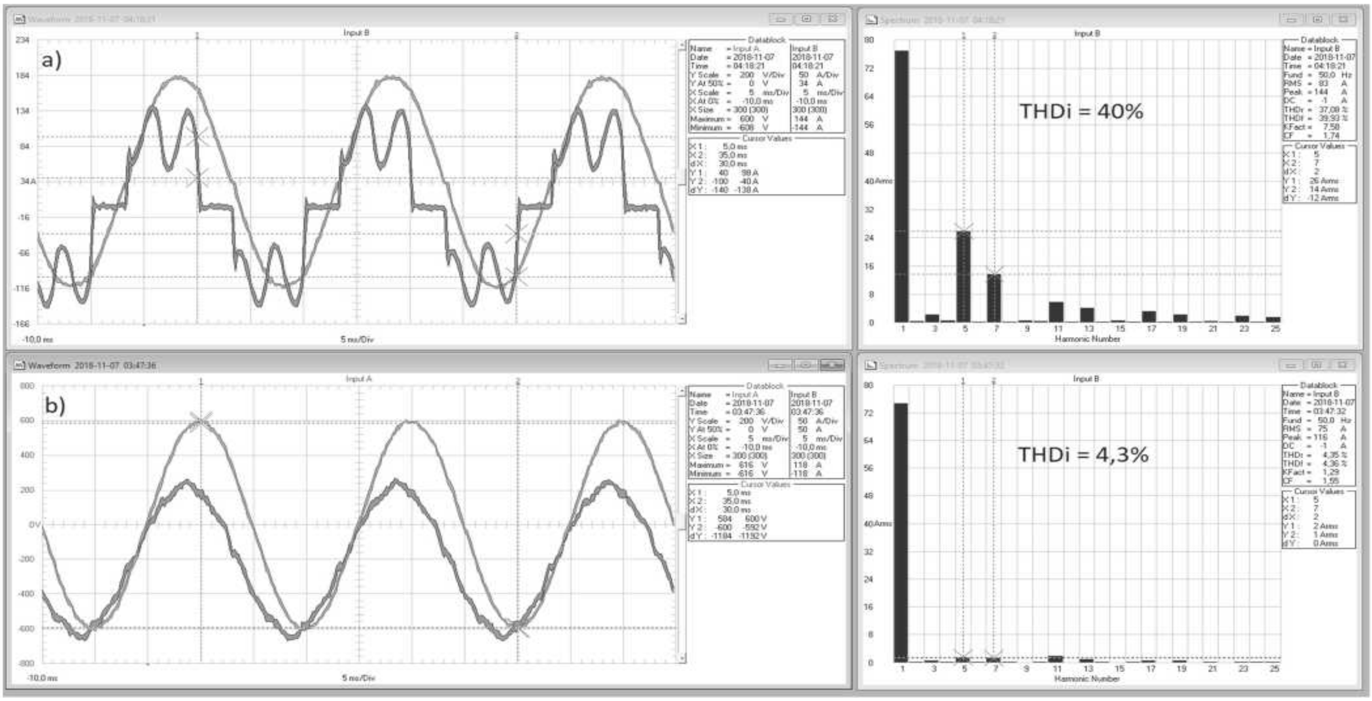

Figure 8. Results of measurement of 55kW converter input current harmonics; a) in the circuit without harmonics filters; b) in the circuit with three-reactor filter with common yokes EF3H-55kW 380-415V±10% T40F [7]

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