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A STUDY ON APPLICABILITY OF A SELECTIVE HARMONIC REDUCTION METHOD FOR A FULL OPERATING RANGE OF A TRACTION INVERTER

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Abstract
The article presents the problem of application of a traction inverter control strategy consisting in selective elimination of harmonics (Selective Harmonic Elimination – SHE) for shaping the spectrum of traction current. The objective of this method is to reduce the conducted disturbances generated by a traction vehicle to the level below admissible values. The selection of the order of harmonics being eliminated from a voltage spectrum influences the values of the remaining voltage harmonics, hence the harmonics spectrum of current consumed from a DC network. The presented study aimed at developing the SHE method to the extent enabling its implementation to the real drive system. The article describes the results compared with limits existing in PKP (Polskie Koleje Państwowe – eng. Polish State Railways), however the presented methodology can be successfully employed for any applicable limits in DC electric traction systems.

Description of the problem

The problem of disturbing influence of traction vehicles in the track circuits of a rail traffic control system was thoroughly examined and described in a number of publications [2],[5],[10],[18],[24].

The article deals with the problem of application of the traction inverter control strategy consisting in selective elimination of harmonics (Selective Harmonic Elimination -SHE) [11],[17],[22] for shaping the spectrum of traction current. The objective of this method is to reduce the conducted disturbances generated by a traction vehicle to the level below admissible values [3],[4]. SHE method implemented into a traction drive system allows for elimination of the selected harmonics from the spectrum of voltage supplying traction motors (V_{out}) [20]. Content of harmonics in traction current (I_d) consumed by a traction vehicle from a supply system depends directly on the voltage harmonics spectrum V_{out}. The selection of the order of harmonics being eliminated from a voltage spectrum V_{out} influences the values of the remaining voltage harmonics, hence the harmonics spectrum of current consumed from a DC network (I_d). In the articles [15],[16], the authors presented the concept of SHE method modification consisting in replacement of selected harmonics elimination with reduction of harmonics to the set level (Selective Harmonic Reduction - SHR). Based on the results of conducted simulation tests, it was shown that the SHR method offers broader possibilities for control of traction current I_d harmonics values. Previous experience of the authors has shown that the SHR method gives positive results that allow for such selection of inverter key switching strategy, so it does not generate disturbances in the frequency ranges used by SRK devices. In previous publication the authors presented an overview of possibilities related to the SHR method application for traction purposes on the basis of a selected operation point of a drive system model. This paper describes the study extended by the analysis of the SHR method effectiveness in a full range of traction inverter frequencies, as it is in the case of vehicle's start-up. Additionally, some limitations related to this method and resulting from the admissible frequency of inverter's keys connections were taken into account.

Admissible levels of disturbances in an electric traction system

Admissible levels of disturbances generated by electric traction vehicles, which were assumed in this paper are defined in [4]. On this basis, the maximum values of I_f current harmonics were established assuming:

- that the drive system under consideration operates in a vehicle powered by 4 individually supplied asynchronous motors,
- there is one input filter of gamma type at vehicle's input with parameters: choke inductance L_f= 8.7 mH; capacitor capacity C_f = 6.5 mF (or a set of filters with corresponding attenuation),
- rms values of current harmonics generated by drive systems of a vehicle add algebraically.

This was a basis for introducing current limits I_f, as defined in Figure 2. The developed limits will constitute a template for disturbances generated by a model of a drive system used further in the paper. Methods of analytical calculation of DC-link current (I_f) can be found in the literature [9],[21]. Due to the use of time domain model of the traction drive, it was decided to calculate DC current harmonics via computer simulation.

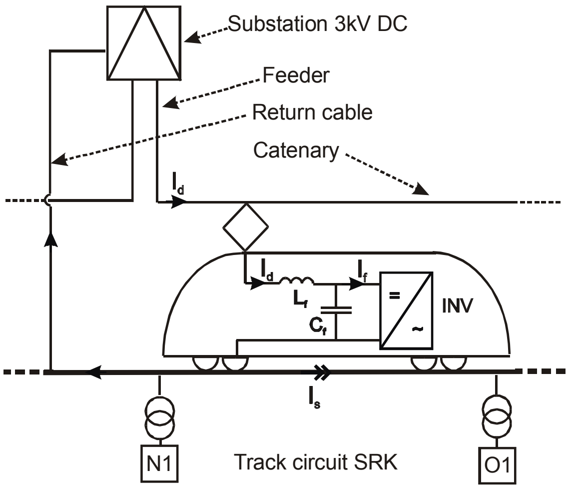

Fig. 1 Supply scheme of a traction vehicle and track circuit in a 3 kV DC electric traction system. I_d – traction current (catenary current), I_f - current consumed by an inverter, I_s – control signal of a track circuit

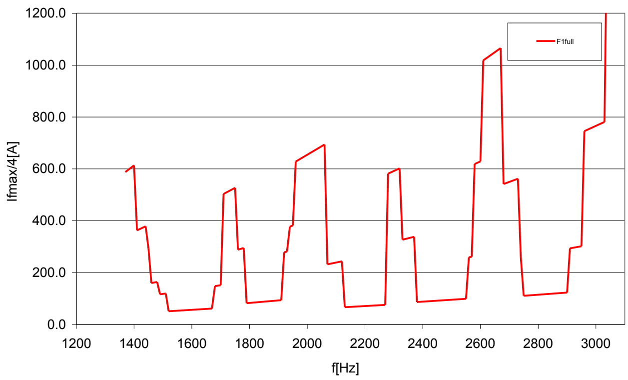

Fig. 2 Assumed limits for current harmonics I_f

Assumed strategy for traction converter control

SHE method as a method for voltage inverter control was widely described in a variety of publications[11],[17],[22]. Publication [20] presents the applicability of the above-mentioned method for traction purposes. The method consists in determining the angle of inverter's keys switching in such a manner, so a traction inverter output voltage wave V_{out} is void of the selected harmonics. The number of eliminated harmonics depends on the number of switching angles as well as voltage wave symmetry. Waves that can be distinguished here include: quarter- and half-wave symmetry and non-symmetrical. The waveform with quarter-wave symmetry was selected for further studies, due to the fact that it is void of harmonics of odd order as well as harmonics being the multiple of number 3. Additionally, with a wave of this type it is necessary to determine only switching angles in a quarter-period (the remaining angles are their mirror image in relation to π and $\pi/2$ - Fig. 3), which limits the number of equations to be solved. The problem of SHE method implementation in a voltage inverter comes down to determination of N switching angles by solving a system of N - number equations:

$$
\begin{aligned}
f_1(k_1, k_2, k_3, \cdots, k_N) &= M1 \\
f_2(k_1, k_2, k_3, \cdots, k_N) &= 0 \\
f_3(k_1, k_2, k_3, \cdots, k_N) &= 0 \\
&\vdots \\
f_N(k_1, k_2, k_3, \cdots, k_N) &= 0
\end{aligned} \tag{1}
$$

where:

$$
f_i(k) = \frac{4}{nhx \cdot \pi}\left[1 + 2\sum_{j=1}^{N}(-1)^k \cos(nhx \cdot k_j)\right] \quad \text{for } i=1,2,3...N \tag{2}
$$

where: k – inverter's keys switching angles, N – number of switching angles in a quarter-period, $M1$ – basic component value of voltage V_{out}, nhx – order of a harmonic eliminated in a given equation

Solution of the above-mentioned set of equations consists in a set of transistors' switching angles, on the basis of which the voltage wave (V_{ster}) that controls inverter's transistors is determined (Fig. 3)

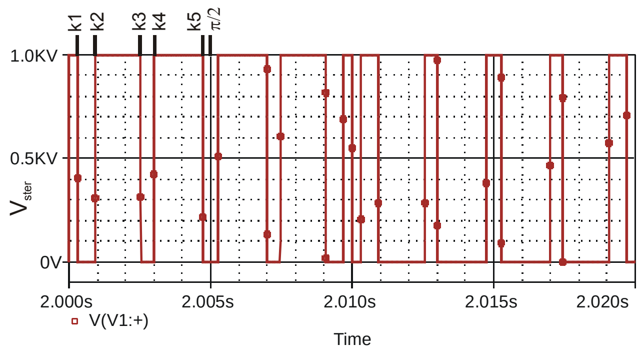

Fig. 3 Voltage wave controlling transistor of the voltage inverter for N=5

The result of implementing the switching angles is a voltage waveform that is void of eliminated harmonics, whose basic component value is $M1$ (1). Fig. 4 shows an exemplary voltage waveform V_{out} obtained by means of computer simulation with the use of the SHE method in a low-voltage model of a traction drive system. The presented example shows the elimination method of harmonics of orders: 5th, 7th, 11th and 13th with a basic frequency f_{fal} = 50 Hz. In the presented case, in voltage harmonics spectrum V_{out} there is no harmonics of frequencies 250 Hz, 350 Hz, 550 Hz and 650 Hz (Fig. 5). Elimination of the mentioned harmonics from voltage V_{out} resulted in elimination of harmonics of 6th and 12th order (300 Hz and 600 Hz – Fig. 6) from current spectrum I_d.

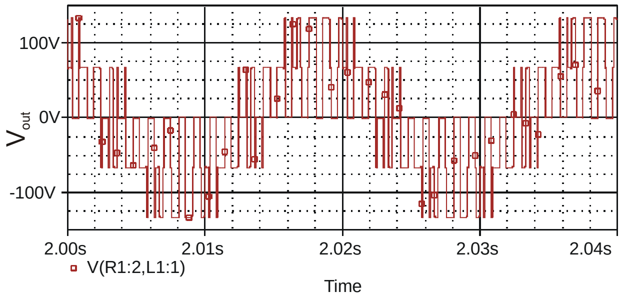

Fig. 4 Voltage waveform V_{out} with the application of the SHE method (results of computer simulation)

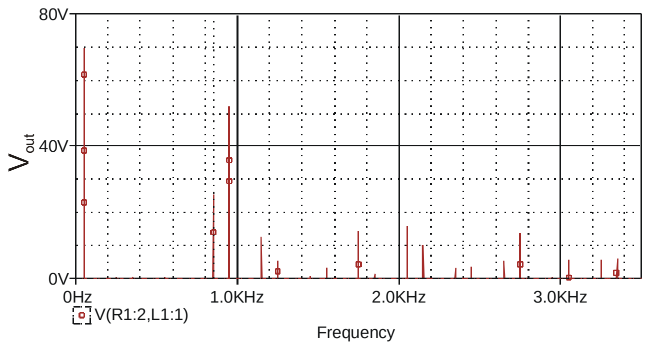

Fig. 5 Voltage harmonics spectrum V_{out}

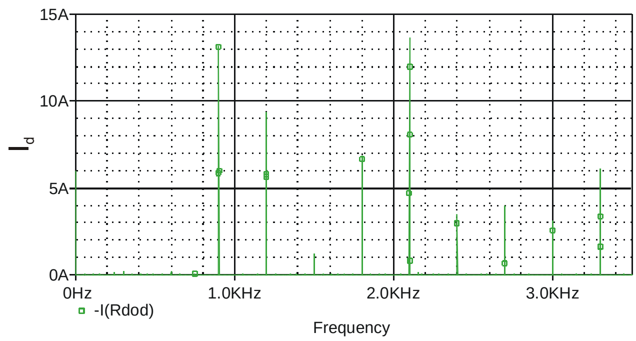

Fig. 6 Current harmonics spectrum I_d

The modification proposed in the paper consists in replacing the right sides of the equation set (1) with a vector of the selected harmonics values:

$$M = [M1; M2; M3; \ldots; MN]^T \tag{3}$$

where: *M1* – basic component value, *M2-MN* – values of voltage harmonics V_{out} that were selected for reduction.

By means of a proper selection of the values from *M2* to *MN*, it is possible to relatively freely shape the voltage spectrum V_{out}, hence current spectrum I_d, which is the basic aim of the paper.). Described method is congruent to the one presented in [1], [6], regarding optimization of harmonics content in inverter's output voltage V_{out}.

Assumptions

The primary aim of the study is to conduct analysis of harmonics spectrum of current I_d consumed from a catenary by an inverter drive system. The analysis is based on the observation of the limit excess of traction current harmonics values (I_f) in the range of frequencies 1300-3200 Hz. Upon identifying the set limit excess by current harmonics, the described method SHR is being introduced (for an operation point, in which the excess has been detected). The aim of the applied method is to maintain the assumed value of the basic component value of inverter's output voltage and to decrease the values of current harmonics I_f to the assigned level.

The exemplary procedure was described on the basis of the selected operation point of a drive system, which was defined by the following parameters: f_{fal}= 35 Hz; *M1*=0.62. Fig. 7 shows the results as well as values of current harmonics I_f and 'F1full' limits presented in one graph. The points were connected with a dotted line so as to increase the readability of a drawing. At first, the SHE method with harmonics elimination was implemented: 5th, 7th and 11th (Fig 7 – red points). It can be observed that values of two harmonics in the examined range of frequencies exceed the assumed level. During examination, no combination of harmonics was found that would allow fulfilling the assumed criterion. The second approach consisted in application of the SHR method proposed by the authors. It was assumed that voltage harmonics of 7th and 11th order would undergo elimination, while 5th harmonic would be reduced to 14% of the value of a basic component. The results of the SHR method application are presented in Fig. 7 (black points). Application of reduction, instead of elimination, allowed for fulfilling the set limits.

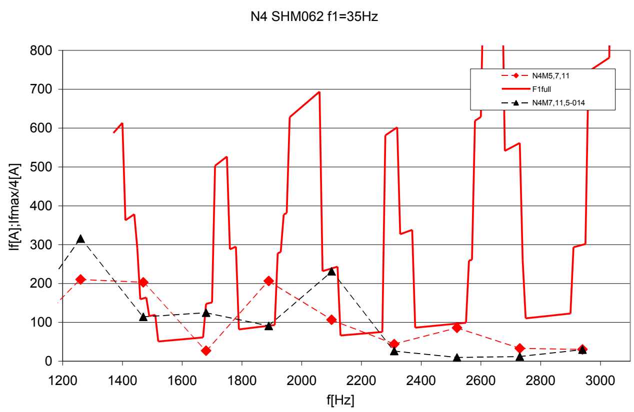

Fig. 7 Current I_d harmonics spectrum with the assumed limits (F1full). Red – SHE, black – SHR

The presented results were obtained by means of computer simulation, based on the assumption that for each point under consideration, a drive system is in a steady-state.

It is essential to take into account the so-called realizability of the established voltage waveform, while determining traction inverter switching angles. The points might constitute the solution for the set of equations, and their implementation in a physical design would have been impossible.

Therefore, the following criteria were considered:

- chronological order of switching angles and limitation in a quarter-period:

$$k_1<k_2<...<k_{N-1}<k_N<\pi/2 \quad (4)$$

- frequency of inverter's key switching resulting from the close proximity of adjacent switching angles cannot exceed the capacity of the real transistors. In the paper, it was assumed that the maximum operation frequency of key f_{tmax}<2 kHz.

$$f_{ti}=\frac{2\cdot\pi\cdot f_{fal}}{(k_i-k_{i-1})} \quad (5)$$

for i=1,2,...,N

where: f_{fal} – frequency of the basic component of inverter's output voltage, k – switch-on angle of inverter's key.

An important issue is variability of the traction vehicle's input impedance as a function of drive system control strategy and input filter parameters. The problem was described in [23] and developed by the authors in [12],[13], [14],[19]. However this issue will not be discussed at presented stage of work.

Results

The above-mentioned approach was used in a full range of the operation frequency (f_{fal}) of the modelled traction inverter. The range of changes f_{fal} was assumed from 5 to 55 Hz with step df_{fal}=5 Hz. The value of inverter's output voltage basic component (V_{out}) increases linearly with f_{fal} in the range from $M1=0.089U_{DC}/2$ to $M1=0.975U_{DC}/2$.

Fig. 8 presents the results of the described analysis of I_f current harmonics in the frequency range from 1200 to 3200 Hz, using the proposed SHR method. Each operation point was considered a separate simulation of a drive system steady state. The application of the described method gave a positive result (all assumed criteria were fulfilled) in each selected operation point. This demonstrates that the described method could be applied in real drive systems in their full range of operation.

Table 1 Voltage harmonics values fixed using SHR method

f_{fal}	N	Values and orders of the harmonics under control					
Hz	[-]	[%] of $U_{DC}/2$					
5.0	6	M1=8.9	M5=0	M7=0	M11=0	M13=0	M19=0
10.0	6	M1=17.7	M5=0	M7=0	M11=0	M13=0	M19=0
15.0	6	M1=26.6	M5=0	M7=0	M11=0	M13=9	M19=0
20.0	5	M1=35.5	M5=0	M7=0	M11=0	M13=10	-
25.0	5	M1=44.3	M5=0	M7=10	M11=0	M61=0	-
30.0	5	M1=53.0	M5=17	M7=0	M11=0	M61=0	-
35.0	4	M1=62.0	M5=14	M7=0	M11=0		-
40.0	4	M1=70.0	M5=5	M7=5	M47=18	-	-
45.0	2	M1=79.8	M31=14	-	-	-	-
50.0	2	M1=88.6	M31=13	-	-	-	-
55.0	2	M1=97.5	M31=5	-	-	-	-

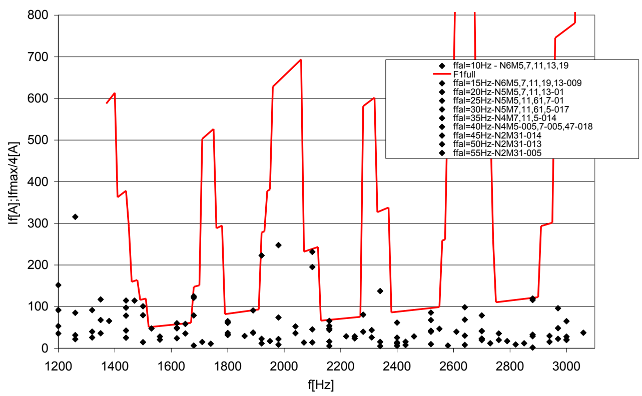

Fig. 8 Spectrum of current harmonics I_f, for frequency f_{fal}=5-55 Hz. black points – current harmonics I_f, red line – assumed limits

Table 1 shows a list of combinations, for each operation point, of V_{out} voltage harmonics being eliminated and reduced, which allow for achieving the required result. Number of switching angles N was changed from 2 to 6 together according to change of frequency f_{fal}. In the majority of cases considered, the correction of one of the harmonics and elimination of the remaining harmonics were sufficient. The only exception was point f_{fal}=40 Hz, where it was necessary to reduce 47th harmonic to 18% and 5th and 7th to 5%. Furthermore, what can be stated is that at low frequencies f_{fal} (in the case under consideration – below 10 Hz), it is sufficient to apply the SHE method (elimination of the selected harmonics without reduction) . Table 2 and Fig. 9 show a summary of switching angles determined for individual operation points of a traction inverter. It constituted a basis for determining frequency (f_t)(Tab.3) of subsequent transistor switching in a quarter-period. As it can be observed, in all cases, frequency f_t is lower than the assumed maximum frequency (2 kHz). The highest frequency of f_{tmax}=1817 Hz. was observed for f_{fal} = 20 Hz. It results from very fast, first in the quarter-period, switching of a transistor $k1$=0.069 rad. The similar case was observed for f_{fal} equal to 25 and 30 Hz. Due to low frequencies of subsequent switching (large angles between subsequent switching), it can be concluded that it is possible (if necessary) to limit maximum frequencies by more even distribution of the switching angles in a quarter-period.

Table 2 Switching angles of an inverter established using the SHR method.

f_{fal}	M1	N	Switching angles					
Hz	[-]	[-]	[rad]					
5	0.089	6	0.265	0.513	0.531	0.775	1.057	1.298
10	0.177	6	0.260	0.498	0.535	0.774	1.066	1.281
15	0.266	6	0.296	0.520	0.575	0.745	1.085	1.304
20	0.355	5	0.069	0.338	0.735	0.990	1.457	-
25	0.443	5	0.076	0.291	0.762	0.969	1.441	-
30	0.530	5	0.112	0.318	0.742	0.982	1.505	-
35	0.620	4	0.176	0.427	0.692	0.942	-	-
40	0.700	4	0.323	0.545	0.851	0.968	-	-
45	0.798	2	0.708	0.969	-	-	-	-
50	0.886	2	0.505	0.763	-	-	-	-
55	0.975	2	0.259	0.556	-	-	-	-

Fig. 9 shows sets of switching angles (in a quarter-period) for the selected operation points of a drive system, which enable meeting the assumptions defined in the paper.

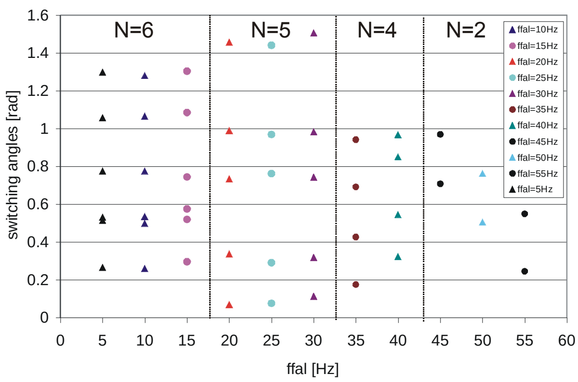

Fig. 9 Switching angles (k) of inverter's keys in the function of f_{fal}, determined by using the SHR method.

Table 3 Frequencies of inverter's keys switching angles of an inverter established using the SHR method.

f_{fal}	N	f_t						
Hz	[-]	Hz						
5.0		118	126	1767	128	111	129	57
10.0	6	241	264	1688	262	215	292	108
15.0	6	318	420	1702	510	283	444	110-
20.0	5	1817	468	316	495	269	545	-
25.0	5	1601	506	296	556	256	598	-
30.0	5	1785	805	460	905	356	1123	-
35.0	4	1271	835	866	895	173	-	-
40.0	4	831	1121	878	1867	201	-	-
45.0	2	358	962	190	-	-	-	-
50.0	2	621	1220	194	-	-	-	-
55.0	2	601	1336	1164				

For the purpose of comparison, analogous studies were conducted using the SHE method and PWM sinusoidal modulation with a carrier wave of frequency f_{tr}=500; 1000 and 1200 Hz. Fig. 10 shows the results obtained using only the SHE method. Previous experience of the authors showed that it is extremely difficult (sometimes even impossible) to select harmonics in such a manner so as to fulfil all the assumptions described in the paper. As it can be seen from Fig. 4, by using the SHE method it was not possible to meet the requirements concerning the range of harmonics between 1300-3200 Hz.

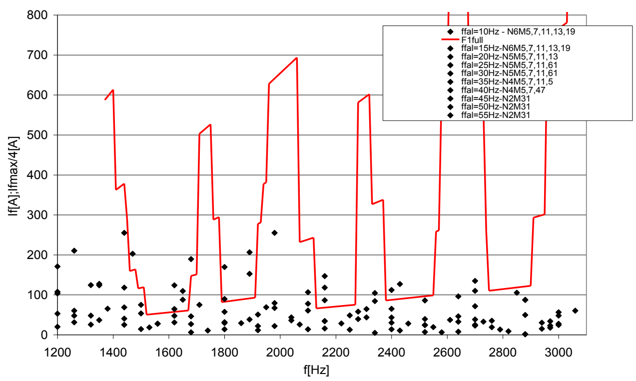

Fig. 10 Current harmonics spectrum I_f using the SHE method.

Fig. 11, 12, 13 present current harmonics spectrum I_f with use of PWM modulation for three frequencies of carrier wave f_{tr}=500;1000;1200 Hz. The most preferred distribution was achieved with high frequency of 1200 Hz, which unfortunately is also associated with the increase of inverter's keys operation frequency.

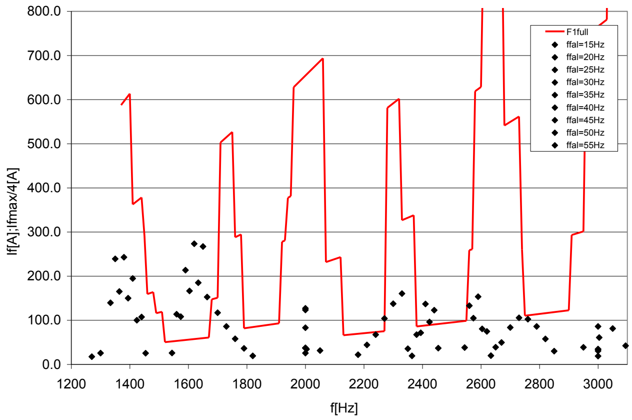

Fig. 11 Overview of current harmonics I_f with the use of sinus/triangle PWM modulation with the frequency of a carrier wave f_{tr}=500 Hz

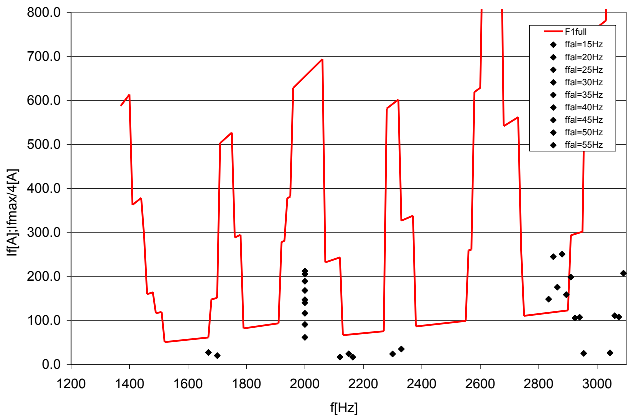

Fig. 12 Overview of current harmonics I_f with the use of sinus/triangle PWM modulation with the frequency of a carrier wave f_{tr}=1000 Hz

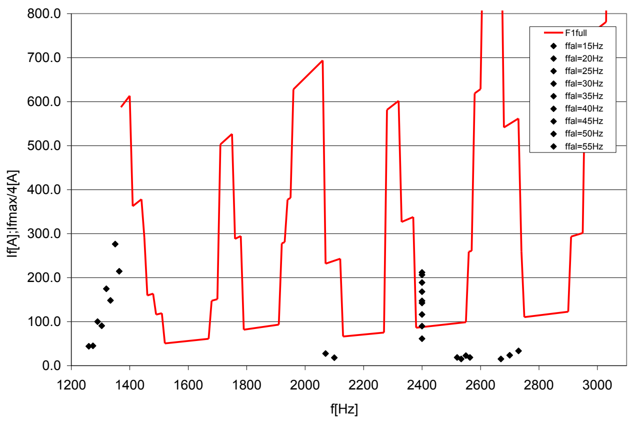

Fig. 13 Overview of current harmonics I_f with the use of sinus/triangle PWM modulation with the frequency of a carrier wave f_{tr}=1200 Hz

Conclusions

The paper discusses the problem of the SHE method application and the possibility of using reduction of the selected harmonics instead of their elimination for the purpose of traction drive control. The implemented method would aim at limiting traction current harmonics to the level defined in the relevant regulations while maintaining traction drive parameters, such as drive torque and rotation speed. The results of simulation tests showed that by expanding the SHE method to the SHR method, as proposed by the authors, it is possible to select for any operation point of inverter drive system such set of switching angles, which would allow for fulfilling both, the criteria of compatibility as well as drive related criteria. Furthermore, factors determining the realizability of the calculation results, such as a maximum frequency of inverter's power transistors switching were taken into consideration. Materials presented in this article also prove that applying only the SHE method is insufficient. The similar approach, taking into account definition of the optimization problem was presented in [1],[8]. However factors applied in these works ware related with the AC side of the inverter, not to the DC side, what is the main goal of presented paper.

The aim of the conducted studies was to develop the SHE method to the extent enabling its implementation to a real drive system. It requires to continue the research towards including many factors occurring in real systems, such as: various levels of supply voltage, abrupt changes of load torque, changeability of fixed drive torque, etc. It also calls for development of various sets of inverter's keys switching strategies using the method similar to the described one as well as establishment of an algorithm allowing for smooth change between the sets together with the change of drive operation point. Naturally, the proposed strategy should cooperate with the currently used strategies for vector control. This method might also be applicable as an intervention method implemented in drive operation ranges, in which it is known that the commonly used methods cause the generation of disturbances for track circuits. The article describes the results compared with limits existing in PKP (Polskie Koleje Państwowe – eng. Polish State Railways), however the presented methodology can be successfully employed for any applicable limits in DC electric traction. Moreover, it is essential, in further work, to take into consideration influence of the parameters of the traction substation to avoid the possibility of resonance conditions between the propulsion system and power supply [7].

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