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25 KV AC RAILWAY LINE WITHIN 3 KV DC INFRASTRUCTURE IN POLAND – ANALYSIS OF OPERATING CONDITIONS

ANALIZA WARUNKÓW WPROWADZANIA DO POLSKIEJ INFRASTRUKTURY KOLEJOWEJ LINII ZELEKTRYFIKOWANEJ W SYSTEMIE 25 KV AC 50 HZ

Abstract

Electrified transport is strongly assorted, due to long term development and use of diversified solutions, particularly in the scope of electrical engineering considering the following aspects: nominal voltage of a power supply system, vehicles' main circuits and electrical drives. The problem of compatible work of varied railway systems in mutual interaction regions, despite of various studies, still appears a significant issue. The main purpose of the paper is to present the negative impact of mutual interaction of AC DC railway regions on the electrified railway lines and power grid. A Matlab – Simulink model of the DC and AC traction systems has been developed. In the article, apart from the main problems which could appear in the AC-DC transition zones, the voltage unbalance analysis caused by the AC traction substation is covered and the influence of asymmetric input voltage of the rectifier traction substation on the DC voltage quality is analysed.

Keywords: traction power supply system, asymmetry, harmonics, mutual influence of AC and DC power systems

Streszczenie

Zelektryfikowany transport jest silnie zróżnicowany ze względu na długi okres rozwoju oraz stosowanie rozmaitych rozwiązań, w szczególności w zakresie rozwiązań technicznych, z uwzględnieniem takich aspektów jak: napięcie znamionowe układu zasilania, główne obwody pojazdów oraz napędy elektryczne. Pomimo przeprowadzenia szeregu badań, problem kompatybilności działania różnych systemów kolejowych na obszarach wzajemnego oddziaływania nadal pozostaje istotnym zagadnieniem. Niniejszy artykuł ma na celu przedstawienie zagadnienia negatywnego wpływu wzajemnego oddziaływania obszarów kolejowych AC-DC na zelektryfikowane linie kolejowe oraz sieć energetyczną. W tym celu opracowano model Matlab – Simulink systemów trakcyjnych DC i AC. W artykule, oprócz głównych problemów, jakie mogą pojawić się w strefach styku systemów AC-DC, przedstawiono również analizę asymetrii napięcia powodowanej przez podstację trakcyjną AC oraz przeanalizowano wpływ asymetrycznego napięcia zasilającego podstacji prostownikowej na jakość napięcia w sieci trakcyjnej DC.

Słowa kluczowe: system zasilania trakcji elektrycznej, asymetria, harmoniczne, oddziaływanie wzajemne systemów zasilania AC i DC

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1. Introduction

High speed railway development requires AC electrification, due to much higher power transfer capacity – vehicles collect lower currents from catenary. As a result, countries previously electrified only with DC system have to deal with mutual interaction of AC and DC systems operating in adjacent areas [1, 3, 4, 6, 11–13]. The latter cooperation and related issues is common in countries that use more than one traction power supply system (e.g. 25 kV AC 50 Hz railway and a tram system supplied from 600 V DC catenary or 15 kV AC 16.7 Hz railway and 750 DC 3rd rail urban system). All these systems must operate with a required high level of safety and reliability, especially in the cities – highly urbanised areas, where the tracks of neighbouring systems are operating in their vicinity [4]. Despite various measures taken, the problem of compatible operation of various traction power supply systems in the contact areas is a significant area of concern and should be taken into account at the first stages of the project.

2. AC and DC railway systems interactions

After introduction of 25 kV AC traction into Polish railway infrastructure, the management of mutual interaction areas will be required. These areas occur at various points of the infrastructure (Fig. 3):

- on the Power Utility System (PUS) side - when traction substations (TSs) of both systems are supplied from the same Point of Common Coupling (PCC). DC TS will be fed by unbalanced voltage whereas AC TS by distorted voltage;
- on the railway side (ERL).

Unbalanced input voltage of DC TS causes fluctuation of its output voltage with doubled PUS frequency (in Poland 100 Hz). Such phenomenon leads to the occurrence of additional, previously not present, non-characteristic higher order harmonics (HH) derived from the operation of a rectifier unit - both on the PUS and ERL sides. As a result, an AC TS connected to the same PCC is fed with lower voltage quality. The latter causes the presence of HH, in the AC TS output as well. Significantly decreased power quality may result in additional issues related to the filtering devices in DC TS – deterioration of the HH filter performance. Installation of two resonance filters tuned to particular rectifier frequencies (600 Hz and 1200 Hz) result in parallel resonance in the middle of those frequencies (Fig. 1). In general, it should not be a problem, however in case of non-characteristic HH presence; further analysis of the filter effectiveness may be required.

Independent bulk supply points for the AC and DC TSs reduces the issues of power quality described above, however, does not resolve the issue related to mutual interaction areas present on the ERL side. Railway lines interact with each other mainly due to [9]:

- inductive coupling – AC ERL has an impact on the DC ERL. 50 Hz voltage (and as a result currents) is present in the DC system circuitry. Additionally, HH currents flowing in the DC catenary may also result in induced voltage (and current) in the AC circuitry. However, this effect is negligible due to relatively low magnitudes of those currents and enough, even small, separation between the AC and DC lines;
- galvanic coupling – return currents of one system may be present in the neighbouring rails of adjacent system. This phenomenon derives from the earthing methodology – the rails of the AC system are well-earthed whereas the rails of the DC system are isolated from the ground (Fig. 3).

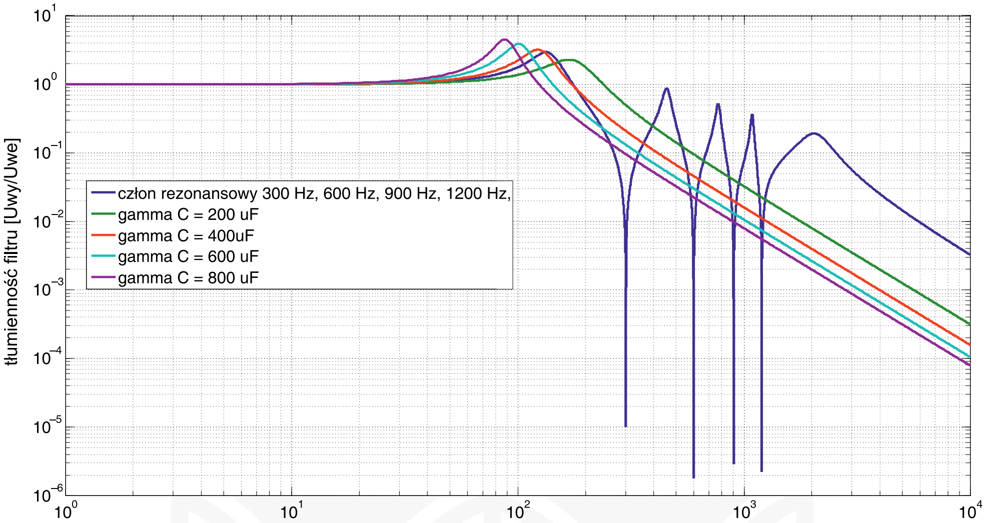

Fig. 1 Exemplary characteristics of the filters used in a DC traction substations in Poland (simulation results)

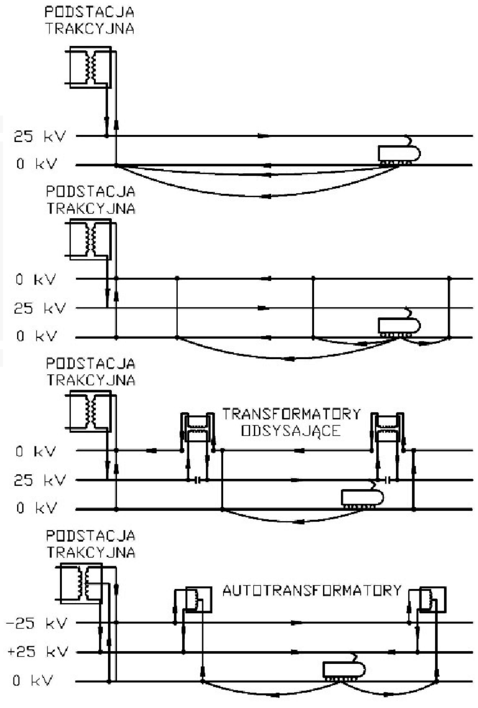

Fig. 2. Current flow in AC traction systems. From the top: 25 kV, 25 kV with a return conductor, 25 kV with return conductor and booster-transformers, 2×25 kV)

Due to inductive coupling, the well-known and safe value of 120 V potential in DC rails [9] is no longer acceptable. This is caused by the influence of AC components, which together (superimposed) with the DC voltage, increase the risk of electric shock (mixed voltages – containing AC and DC components [9]). 50 Hz component induced in DC rails can also have a negative impact on the operation of older types track circuits (TC), which operate on the basis of isolated blocks. Additionally, due to galvanic coupling, the 50 Hz component may occur in DC rails (together with an induced component). Depending on the type of an AC system (25 kV, 25 kV with a return conductor, 25 kV with a booster-transformers or 2×25 kV), the negative impact of galvanic coupling seen from the DC systems changes, due to the amount of return current flowing in the earth (Fig. 2).

As far as the adjacent operation of PUS lines and ERL is concerned, described above description may be applicable as well.

Galvanic coupling results in the significant impact of the DC system on the AC system – DC component present in the AC rails not only increases the risk of electric shock (mixed voltage [9]), but also negatively influences an AC system infrastructure equipment (transformers, booster-transformers and autotransformers cores saturation). DC stray currents flow path is closed by the elements of the adjacent AC system infrastructure.

If the mutual interaction areas appear at both PUS and ERL side (e.g. AC and DC TSs are supplied from the same PCC and ERLs operate in close proximity), the level of negative interference, described above, may be higher.

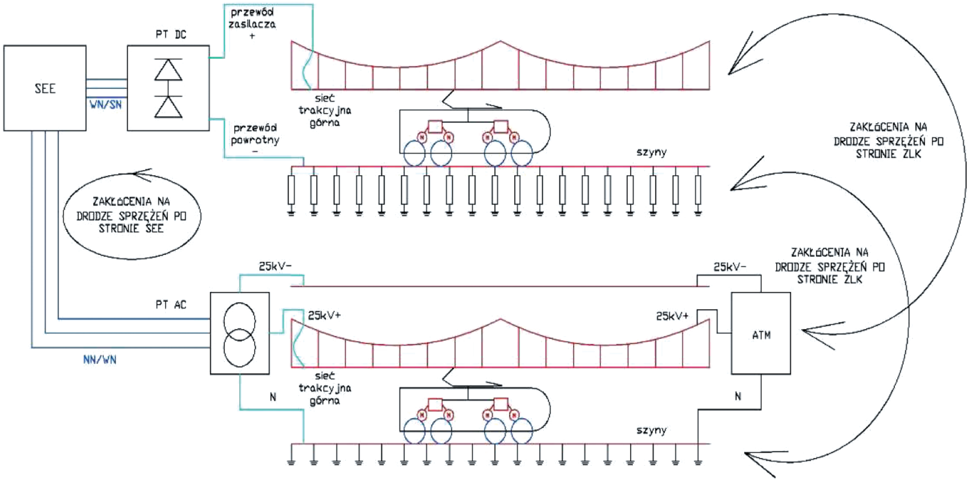

Fig. 3. Mutual interaction areas of neighbouring AC and DC railway systems

3. Analysis of voltage unbalance at the PCC feeding AC TS

Feeding diagram (Fig. 4) was proposed for the exemplary analysis of the PUS side mutual interaction areas. AC TS supplies two railway sections (25 km each) – left hand side (to AC TC 2) and right hand side (to sectioning post) –50 km in total. For the purpose of this analysis sectioning posts and sub-sectioning (paralleling) posts between AC TSs have not been presented on Fig. 4. Fig. 5 shows the TS AC output power during a peak period under normal feeding conditions (when neighbouring TS is in operation). The knowledge of the power demand curve will be significant to assess the minimum short-circuit power (fault level) at PCC busbars which is required to meet the unbalance requirements described in regulations [10].

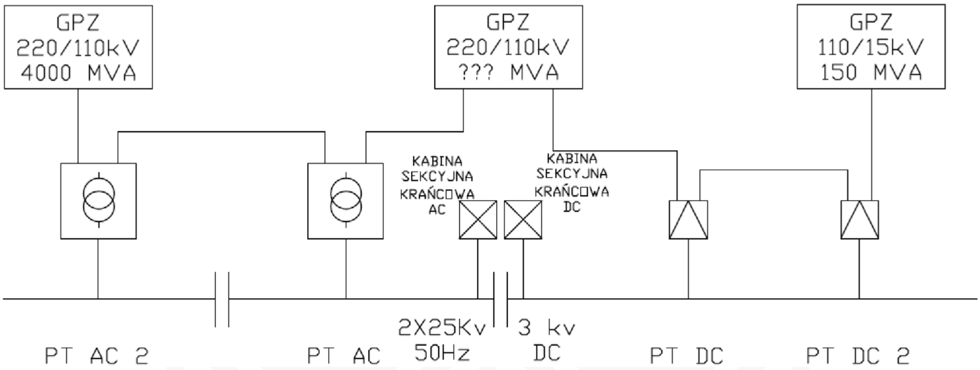

Fig. 4. Contact area of AC and DC railway systems at the PUS side (AC and DC TSs supplied from the same PCC)

Relevant regulations governing maximum levels of voltage unbalance in Poland [8, 10]. Polish regulation states that [10]: "…Within each week, 95% of results from the set of 10-minute average RMS values of a negative phase sequence voltage component should be in the range of 0% to 1% of a positive phase sequence voltage component".

The ratio of the RMS value of a negative phase sequence (nps) voltage component to the RMS value of a positive phase sequence (pps) voltage component is defined as a voltage unbalance coefficient α_u [2, 6, 8, 9]. RMS value averaged over 600 s window is understood as a one value (calculated from the set of instantaneous values in 10 minutes window) mentioned in the regulation [10]. One week comprises of 1008 of the latter values, what means that 95% of α_u values (RMS) must be smaller than 1% – it constitutes 958 values. Therefore, if it is assumed that a peak period lasts for 8 h per day (2×4 h), then the peak period constitutes 33% of overall time (8×7 = 56 h). In the analysed case, the exceedance of α_u may occur only during a short peak hour periods. If during all of the peak periods the α_u values calculated in line with the requirements [10] are higher than 1%, then only 67% of those values will be acceptable (from the required 95%). In such case, to be fully compliant with the requirements set out in regulation [10], duration of the peak period should be no longer than 1.2 h. The overall power supply system for AC railways should be designed properly (with possibly high short circuit power at the TS HV busbars) to provide the envisaged level of voltage unbalance (up to 1%) throughout the required period (min. 95% over the week).

Taking into account the forecasted traffic, one defined power demand of an AC TS and performed the analysis of mutual interaction of the AC and DC railway systems at PUS side (the same PCC supplies DC and AC TSs). The first step was to provide such short-circuit power at the AT TS HV busbars that, for a given power demand curve (Fig. 5), TS will not introduce unacceptable [10] voltage unbalance.

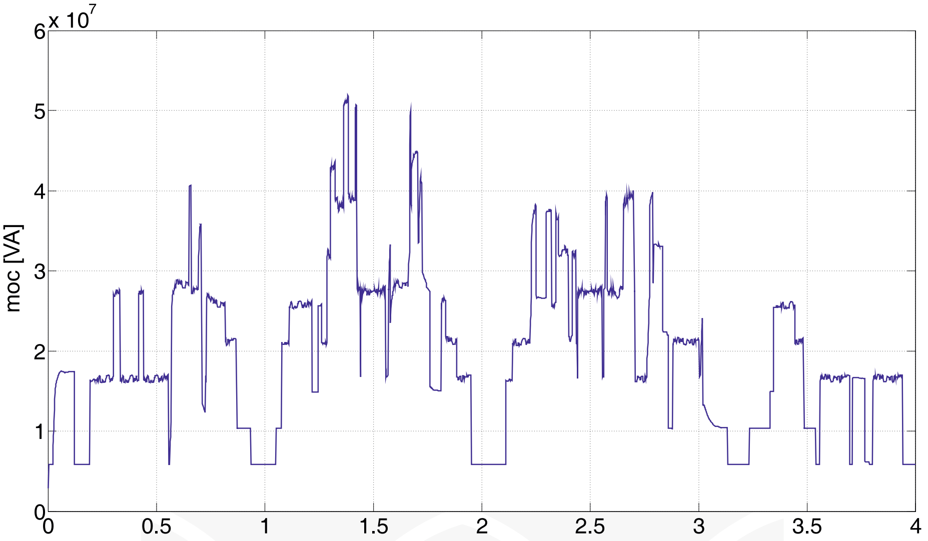

Fig. 5. Forecasted load of an AC TS – 4-hour peak period [11]

Figure 6 shows how many of the 10-minute values (described in [10]) exceed the permissible limit versus the short-circuit power (fault level) at the PCC. Figure 7 confirms that the voltage unbalance, caused by the AC railway operation, is acceptable when minimum short-circuit power at PCC is at least 3 GVA. In this case the voltage unbalance level at the PCC busbars will be up to 1% (Fig. 8) [of course if no unbalance comes from the PCC upstream side].

Therefore, as far as the voltage unbalance is concerned, the short-circuit power at the PCC should be the considered as the most significant area of analysis.

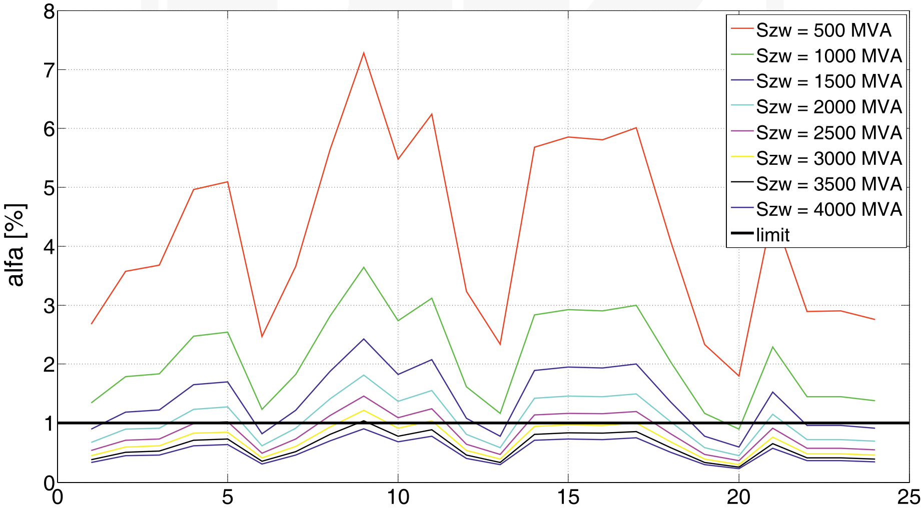

Fig. 6. Exceedance of the 1% unbalance α_u limit for various fault levels (short-circuit powers) at PCC (busbars) feeding the AC TS

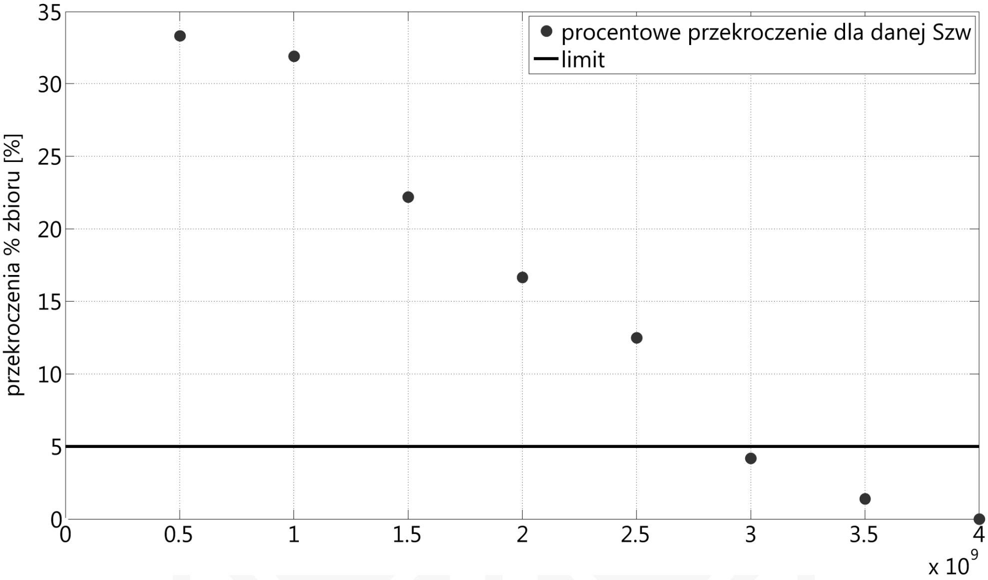

Fig. 7. Exceedance of the 5% limit by 10-minute sets of RMS values αu during a week, for various fault levels (short-circuit powers) at PCC (busbars) feeding an AC TS

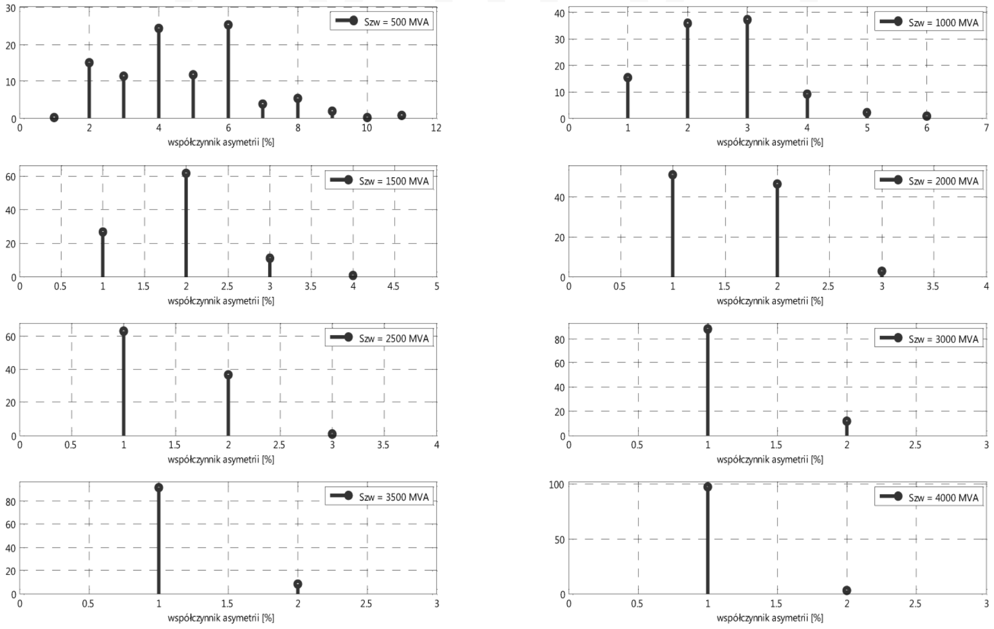

Fig. 8. Estimated contribution (%) of instantaneous (5-seconds) values of α_u factors during a 4-hour peak period [if the value is equal to 1 it means that α_u is within the range of 0–1 %] for various fault levels (short-circuit powers) at the PCC

4. Voltage quality analysis at the AC and DC ERL side in case of the same PCC for AC and DC TSs

Even if AC TS is compliant with the regulation [10] (acceptable voltage unbalance level), input voltage of DC TS will not be fully balanced. This phenomenon results in the occurrence of non-characteristic HH in both AC and DC side (input current and output voltage respectively) of this DC TS. The magnitudes of HH depend on the commutation angle of the rectifier diodes and therefore on the DC TS load.

For the purpose of the latter voltage quality analysis (AC and DC TS are supplied from the same PCC), one has developed a MATLAB – Simulink model with the SimPower library application. In line with the previous analysis, the 3 GVA PCC was modelled to supply AC and DC TS. DC TS output power is around 6 MW, whereas the power consumed by the AC TS is equal to 40 MVA (what causes asymmetry at the PCC around 1.3%). The following figures (Fig 9, 10) show HH present in the input current and output voltage of the DC TS. Fig. 11 demonstrates the HH present in the output voltage of the AC TS (note: this analysis do not take into account the harmonic footprint caused by the rolling stock).

As previously mentioned, the presence of non-characteristic HH in a DC system can cause serious complications [1] related mainly to the operation of signalling systems and filters in a TS [5]. LC filter may be considered as a solution [7]. In the AC TS input voltage, if TS is supplied from the same PCC as neighbouring DC TS, the contribution of HH is increased as a result of the voltage unbalance (Fig. 11). From the point of view of the PUS, electric traction, both AC and DC, is seen as so-called ‘disturbing and unstable’ load [2]. Therefore, HH in the AC ERL are present when a DC TS operates under loading and finally, non-characteristic HH occur in DC TS rectified voltage only when AC TS is in operation. If both TSs (AC and DC) are loaded at the same time the results of a shared PCC will be present at both, AC and DC side of the ERL.

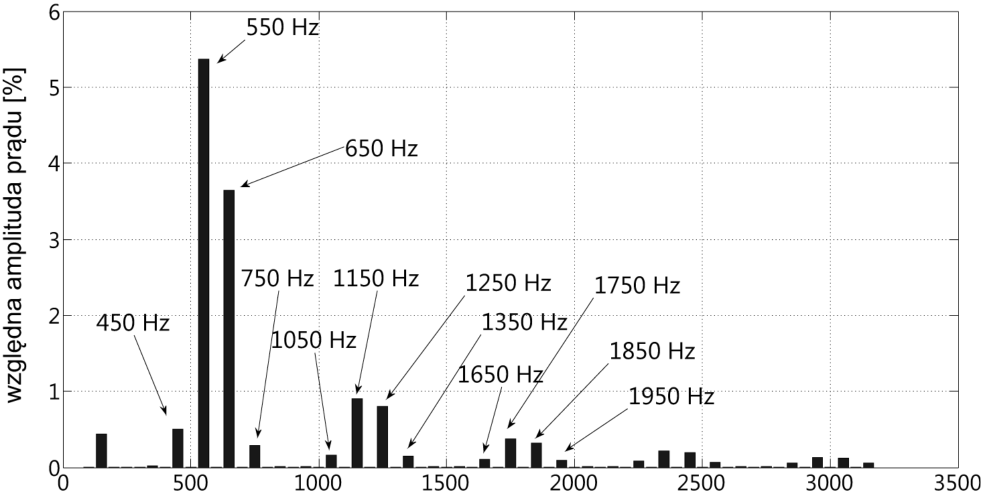

Fig. 9. Current magnitudes of HH in AC current supplying a DC TS, related to 50 Hz fundamental [PCC short-circuit power 3 GVA, α_u =1.3%]

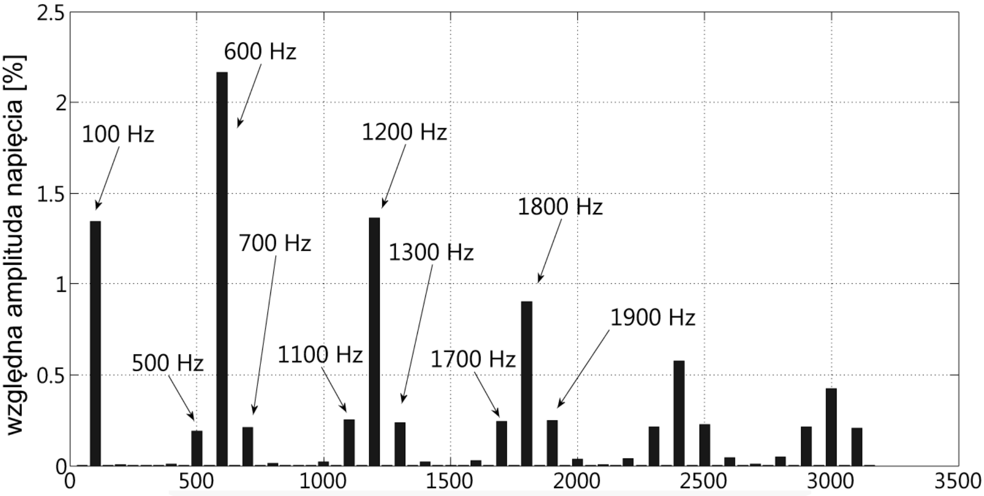

Fig. 10. Output voltage magnitudes of HH in a DC TS, related to the DC component [PCC short-circuit power at 3 GVA, α_u =1.3%]

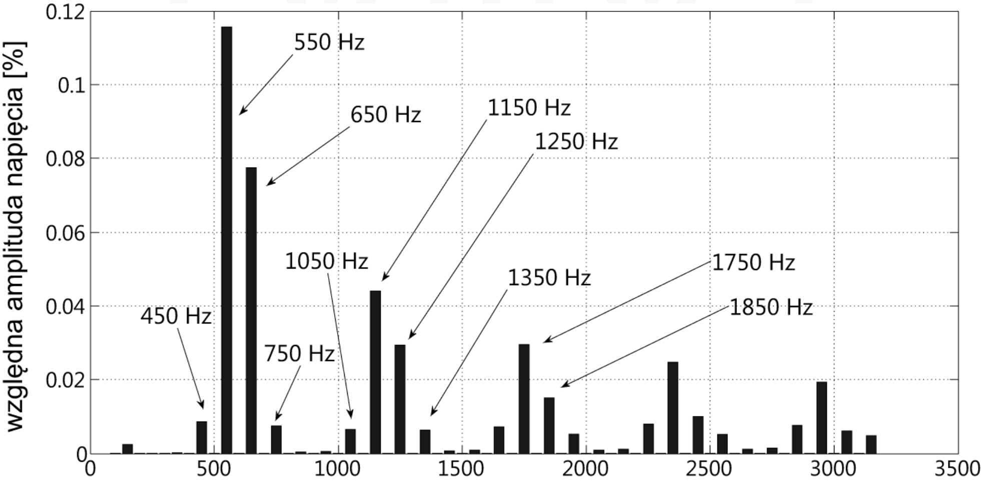

Fig. 11. Output voltage magnitudes of HH in an AC TS [PCC short-circuit power 3GVA, α_u =1.3%]

5. Conclusions

The introduction of the railway line electrified with 25 kV AC 50 Hz voltage into Polish railway infrastructure might lead to appearance of AC and DC mutual interaction areas. Phenomena occurring in these areas must be taken into account at the concept design stage of the project. Provision of independent and reliable operation of both lines proves to be insufficient in the mutual interaction areas. It is important to take into consideration certain issues, such as malfunction of infrastructure equipment due to neighbouring system interference, increased risk of electric shock (mixed voltages – AC and DC), deterioration of voltage quality in the PUS at the PCC and in AC and DC traction networks (additional harmonics). When introducing a new 25 kV AC railway line into the 3 kV DC infrastructure area in Poland, it is necessary to conduct an additional and comprehensive research and analysis, which will employ a complex approach to the contact areas' related phenomena.

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