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Analysis of input impedance frequency characteristic of electric vehicles with a.c. motors supplied by 3 kV DC system for reducing disturbances in signalling track circuits caused by the harmonics in the vehicle's current

Abstract: *The paper presents the results of an analysis of input impedance of electric traction vehicles powered by asynchronous motors, supplied by 3kV DC system. Input impedance of a traction vehicle is a parameter defined by appropriate norms affecting the insurance of compatibility between a traction vehicle and an electric traction supply system and track circuits of a railway traffic control system. The results presented in the article show that there are parameters of a traction vehicle main circuit, for which a module of vehicle input impedance is not a constant value and changes according to the inverter's operation point. Additionally, studies were conducted to determine whether input impedance of a traction vehicle fulfils specified requirements depending on the parameters of the applied input filter and minimum required value of impedance module.*

Streszczenie: *. W artykule przedstawiono wyniki analizy impedancji wejściowej elektrycznych pojazdów trakcyjnych napędzanych silnikami asynchronicznymi, zasilanych z systemu trakcji 3 kV napięcia stałego. Impedancja wejściowa elektrycznego pojazdu trakcyjnego jest parametrem określonym odpowiednimi normami mającym wpływ na zapewnienie kompatybilności między pojazdem trakcyjnym, systemem zasilania trakcji elektrycznej a obwodami torowymi systemu sterowania ruchem kolejowym. Wyniki przedstawione w artykule dowodzą, że istnieją parametry obwodu głównego pojazdu trakcyjnego, dla których moduł impedancji wejściowej pojazdu nie jest wartością stałą i zmienia się wraz ze zmianą punktu pracy przekształtnika. Dodatkowo przeprowadzono badania mające na celu określenie czy impedancja wejściowa pojazdu trakcyjnego spełnia określone wymagania w zależności od parametrów zastosowanego filtru wejściowego i minimalnej wymaganej wartości modułu impedancji. (**Analiza charakterystyki częstotliwościowej impedancji wejściowej pojazdów trakcyjnych z silnikami prądu przemiennego zasilanych z sieci 3 kV DC w celu ograniczenia zakłóceń w obwodach torowych powodowanych harmonicznymi prądu pojazdu**)*

Keywords: input impedance, traction vehicle, asynchronous drive, EMC, track circuits,
Słowa kluczowe: impedancja wejściowa, pojazd trakcyjny, napęd asynchroniczny, EMC, obwody torowe

Introduction

In recent years, the problem of electromagnetic compatibility has gained significance in the broadly defined area of railway transport. This phenomenon is closely related to the wider application of the modern accomplishments of electronics and power electronics in the modern traction vehicles.

EMC problem in the electrified transport

By electromagnetic compatibility, in relation to the railway electrified transport, is defined the area of issues concerning the interactions between devices belonging to the system of electric traction as well as between railway devices and other devices, operated in the vicinity (internal and external compatibility). Due to the technical specificity of the railway environment for all these devices there must be specified both levels of electromagnetic disturbances emission as well as the resistance to disturbances received from other devices in the wide range of frequencies (from the frequency below 50Hz, used by the signalling and control system (SRK) system up to frequencies of the radio bands) [2]. It is also significant to properly define the crucial parameters [3, 11].

A particularly important but difficult to achieve is lack of disturbances generated by the high-current circuits of vehicles and traction electrical power engineering (power up to a dozen MW) of the low-current circuits (power up to several MW), which are a part of the control and signalling traffic system. The main sources of electromagnetic disturbances are the following devices: traction rectifiers (harmonics of the rectified voltage of a substation) and traction vehicles equipped with power electronics converters (current harmonics).

Compatibility of electric traction constitutes a very broad issue, covering a considerable range of engineering disciplines. Specificity and complexity of the problem of compatibility in this very case is a result of the following reasons, formalized in the norms PN-EN 50-121 [12]:

- high variety of supply systems,
- changeability in the electric energy demand as well as vast assortment of the control and command system,
- high power supplied by collectors from contact line to the movable receivers-traction vehicles,
- high-speed vehicles,
- possibility of occurrence of movable sources of various types of disturbances in the one sphere of influence,
- difficult to anticipate current distribution of a system load, return current flowing through the ground (stray currents), in particular,
- possibility of occurrence of disturbances from various sources at the same time,
- generation of the electromagnetic disturbances in the wide range of frequencies and energy,
- interaction between a supply system and reception, which might result in both amplification and weakening of the emerging disturbances.

It is also important to remember about the cases of application of various generations devices (e.g. modern vehicle with track circuit of the old type) a common course of signalling and supplying cables, the complexity and linkage of subsystems [4].

Input impedance of a vehicle

Input impedance of an electric traction vehicle is a parameter that value determines the level of transfer of disturbances from a contact line to a return circuit used by the devices of low power of a railway traffic control. It can be concluded that input impedance of a traction vehicle is a parameter based on which one can assess the possibility of occurrence of higher harmonics in current collected by a vehicle and flowing through a return circuit, which might disturb the operation of track circuits. Therefore, this parameter should be determined at a vehicle design stage and its value should be known in the whole range of operation of a drive system.

Taking into account the above mentioned issues, it can be stated that the problem of input impedance of a traction vehicle supplied from the catenary of direct current as a parameter describing the electric traction vehicle, is an issue from the group of internal compatibility matters. This concerns, in particular, the interfering disturbances between traction current of values in the range of kA in the return circuit (rail) of a vehicle supply circuit and the track circuits used by the railway traffic control system, which use rails for the signal transmission (values in the range of mA).

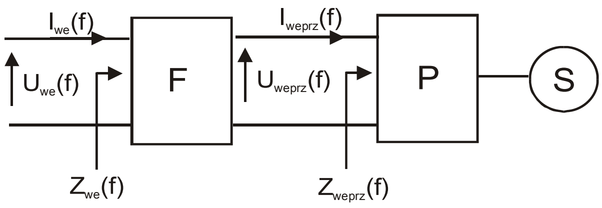


Fig. 1 Schematic diagram for identification of current and voltage measurements points necessary for determination of input impedance:-F- converter input filter; P-converter; S-traction motor

Input impedance of a traction vehicle

In this paper the concept of traction vehicle input impedance for a given frequency is understood by the author as quotient of voltage U_{we} (f) and current I_{we} (f) determined for the frequency f by distribution of time runs U_{we} (t) and I_{we} (t) in the Fourier series with application of the FFT function available in the simulation package in use. The condition for proper determination of the input impedance in the described manner is the selection of a drive system operation point, so that at this point a drive does not generate current component of f frequency [7]. The essence of such an analysis is determination of the value of current collected by the system resulting only from voltage excitation from the feeder's side without a component derived from the side of a drive system. The method, preceded by literature research on determination of drive systems' input impedance [9], [10] has been verified by application of measurements and described in [15].

Simulation model for determination of input impedance of a traction vehicle powered by asynchronous motors.

For the purposes of the analyses, conducted in the paper, a circuit model of an asynchronous motor supplied from a voltage inverter has been chosen. The model incorporates resistance and inductance of dissipation of stator's windings, resistance and inductance of dissipation of rotor's windings calculated into the side of stator and parameters of magnetisation branches. While modelling the motor, the constancy of windings' parameters over the operation range has been assumed.

A model of a voltage inverter, made for the purposes of operation/paper, constitutes another element of a drive system model. This model consists of a system of power electronics connectors, an input filter and control [14]. The analysis is restricted to the steady states of a drive system, thus a controller made for the purposes of operation, allows the setting of frequency of a basic voltage harmonic, frequency of pulse width modulation and depth of modulation, which at the analysed operation point (during calculations) remain constant. There has been introduced a short-circuit protection in the inverter's branch, caused by simultaneous conduction of the upper and lower branch key. This protection consists in the introduction of different voltages of the lower and upper key release by a controller with a certain margin, which allows for attainment of inverter dead time of 0,87μs. The following values characterising the control, have been defined on the basis of the runs from fig. 2.

Modulation depth PWM M_{mod}:

(1) $$M_{\mathrm{mod}} = \frac{V_{\sin}}{V_{tr}}$$

where: V_{sin} [V] -amplitude of a sinusoidal signal, V_{tr} [V] - amplitude of a triangular signal

Modulation frequency f_{mod}:

(2) $$f_{\mathrm{mod}} = \frac{1}{T_{tr}}$$

where: T_{tr} [s] - period of a triangular signal

Frequency of basic component of inverter output voltage f_{fal}:

(3) $$f_{fal} = \frac{1}{T_{\sin}}$$

where: T_{sin} [s] - period of a sinusoidal signal

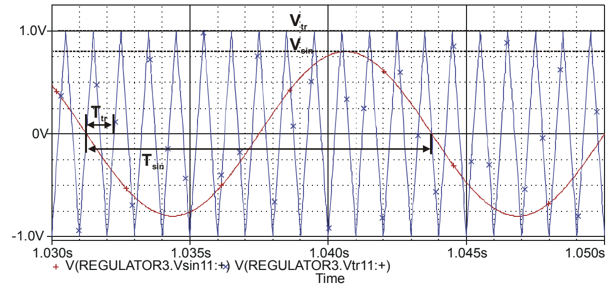


Fig. 2 Runs of signals compared to the generation of runs which control inverter branches, where: V_{sin}- an amplitude of sinusoidal signal, V_{tr} – an amplitude of triangular signal, T_{sin} - a period of sinusoidal signal, T_{tr} – a period of triangular signal

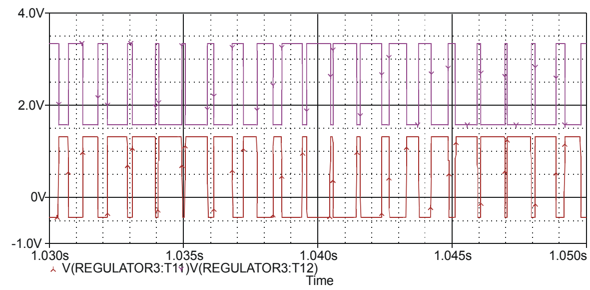


Fig. 3 Exemplary runs of the signals controlling the "upper" and "lower" key of an individual inverter branch

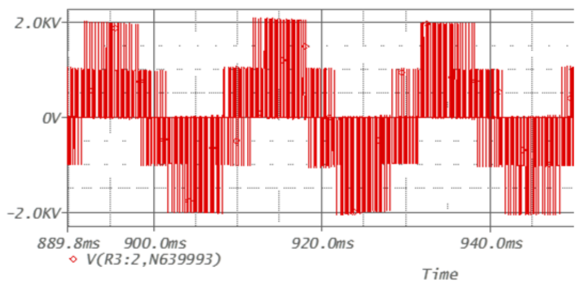


Fig.4 Exemplary runs of phase voltage with a 3-phase supply of load of type RL by a voltage inverter with PWM modulation

The following simplifications have been made:

– the semi-conducting elements of a converter have been replaced with ideal connectors

– the shape of voltage wave is defined at the beginning of simulation and remains constant during simulation

– the model has been supplied by an ideal source of constant voltage U_{DC} with a variable component U_h,

– a basic component of inverter output voltage with PMW option has been changed proportionally to the frequency change of the first harmonic of output voltage.

– modulation frequency had constant value for each of the simulation series

Exemplary results of the measurement verification of the selected model of a drive system have been presented in fig. 6. Verification is based on the comparison of results of determination of input impedance module of a drive system under laboratory conditions (fig. 6-pom) with the results obtained by a computer simulation (fig 6.-sym).

Examples of determination of input impedance of vehicles powered by asynchronous motors

The above described model of a traction system, which consists of voltage inverter and asynchronous motor, has been used for determination of input impedance of a single drive group of a vehicle and equipped with a motor of the following rated values:
P_{mech} = 500 kW - mechanical power, U_n = 2000 V - rated voltage, f_n = 60 Hz -rated frequency, I_n = 170 A - rated current.

Scheme of the main circuit of the drive group under consideration is presented in fig. 5

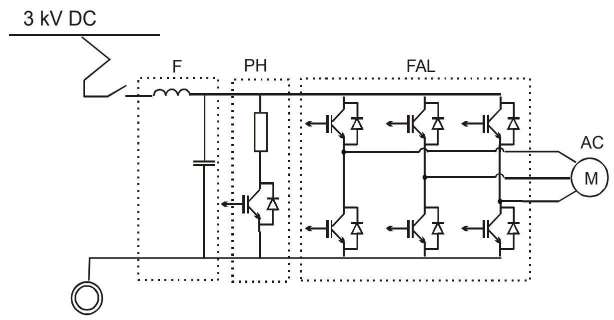
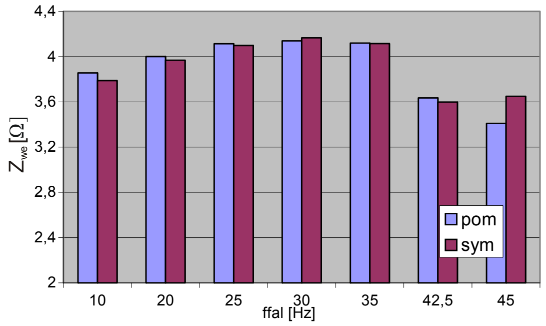


Fig. 5 Exemplary scheme of main circuit for one driving group of a vehicle powered by asynchronous motors supplied by voltage inverter AC/DC.

Figures 7 and 8 present the changeability of input impedance of a drive system and the change of inverter operation frequency f_{fal} or variable and constant depth of modulation M_{mod}. Additionally, the impact of depth changeability of modulation on the module of input impedance of the analysed drive system (fig. 9) has been analysed.

Main circuit of a vehicle powered by asynchronous motors usually consists of several such groups, connected in parallel. The case considered in this point, applies to the situation in which one traction motor is supplied by one voltage inverter (individual power supply). Input impedance of the whole vehicle is the impedance from the one drive group divided by the number of groups that power a vehicle.

It was decided to conduct simulation for one such group, due to the both, considerable time reduction as well as the possibility of equipping a vehicle with a various number of groups, depending on the function and construction of a vehicle.



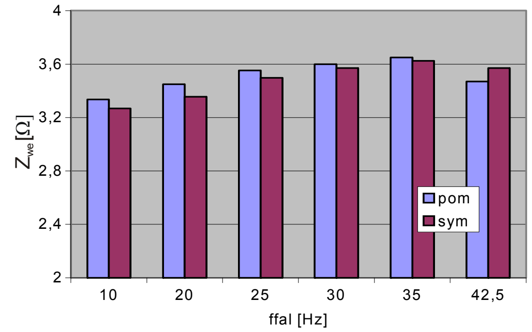


Fig. 6 Comparison of the results of impedance module determination by computer simulation (sym) with the results of laboratory measurements (pom) for various frequencies of converter operation (f_{fal}) ith inductance of input filter L_{F1} = 1,8mH a) impedance for harmonic 41 Hz b) impedance for harmonics 46 Hz

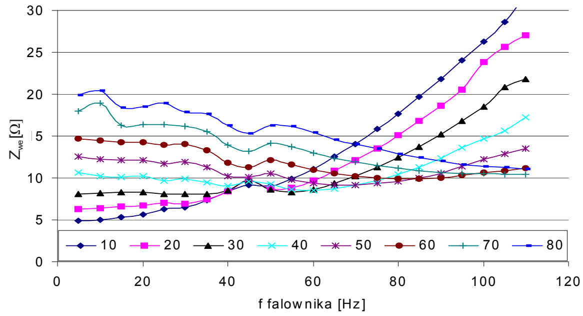


Fig. 7 Runs of system input impedance module for selected frequencies in the function of inverter operation frequency f_{fal}.

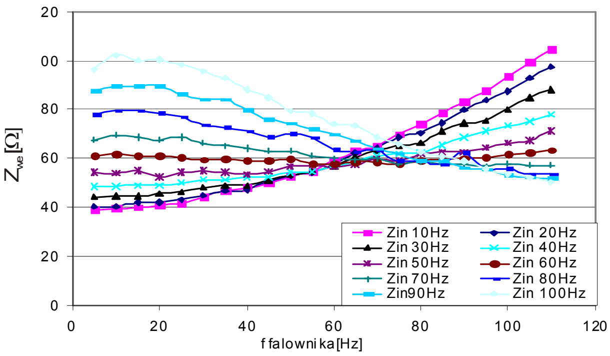


Fig. 8 Module of input impedance of a drive system in the function of inverter frequency f_{fal},, for selected frequencies with constant depth of modulation M_{mod}=0,6

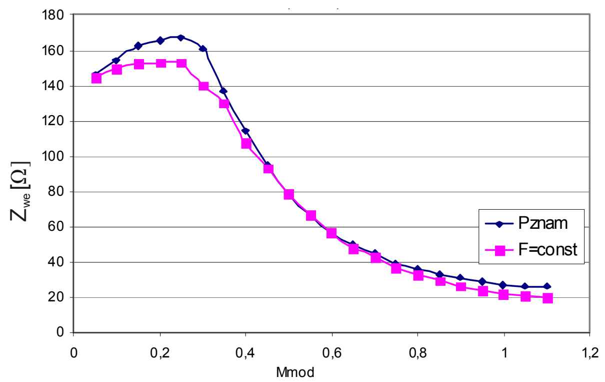


Fig. 9 Module of input impedance of a drive system in the function of modulation depth for the frequency of 50 Hz, where: P_{znam} - frequency of an inverter that changes fluently together with modulation depth F_{const} - constant inverter frequency

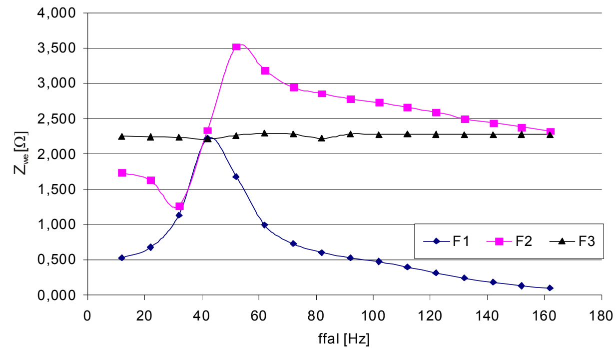


Fig. 10 Results of determination of input impedance module in the function of frequency of one drive group for three versions of an input filter F1 (L_f = 8,7 mH, C_f = 1 mF); F2 (L_f = 16 mH, C_f = 1 mF); F3 (L_f = 8,7 mH; C_f = 6,5 mF)

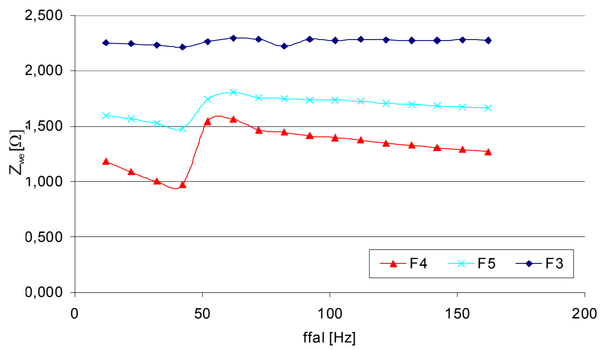


Fig. 11 Results of determination of input impedance module of one drive group for three versions of an input filter F4 (L_f = 8,7 mH, C_f = 2 mF); F5 (L_f = 8,7 mH, C_f = 2,8 mF); F3 (L_f = 8,7 mH; C_f = 6,5 mF)

Results of impedance determination of the described system by computer simulation for frequency 50Hz are presented in fig. 10 and fig. 11. Simulations have been conducted for various versions of the input filter (F1, F2, F3, F4, F5) with different values of inductance and capacitance (marked as L_f and C_f). In fig. 10 substantial influence of the input filter with low filter capacitance(C_f = 1 mF) can be observed. Increasing the filter inductance from 8,7 mH to 16mH has not limited the impedance fluctuation of a drive group in the function of inverter frequency , but allowed for the setting of impedance at the relatively high level of 2,2 Ω at higher motor speeds. Application of the "F1" filter causes a rapid decrease in impedance values together with a change of basic harmonic frequency of inverter voltage. Additionally in the diagram (fig. 10) there is impedance for "F3" filter with much higher input capacitance (C_f = 6,5 mF). This system can be characterised by constant impedance in the analysed range of values of about 2,2 Ω. This value can be insufficient when connected to a larger number of groups equipped with this filter [5]. Fig. 11 presents the results for solutions equipped with filters marked as F4,F5,F3. It is an analysis of an impact of input filter capacitance on the impedance run of the analysed drive system. On the basis of a diagram it can be concluded that system impedance together with the increase in filter capacitance grows and its changeability reduces together with a change of inverter operation frequency. For considerable values of capacitance, which are used in these types of solutions (C_f = 6,5 mF) with filter inductance 8,7 mH, impedance reaches the constant value of 2,2 Ω.

According to the previously valid norm PN-EN 50388 [13], which defined the minimum admissible value of the input impedance module of converter traction vehicle at the level of 2 Ω, F3 filter allowed for application of only one drive group in a vehicle from the presented groups. The new standard defines this value at the level of 0,3 Ω , which means that in the light of new regulations it is possible to use 7 drive groups with F3 input filter in one vehicle. In practice, it means that this system can be used both in 6- and 4- motor vehicles. In the case of multiplied traction of 4-motor vehicles the parameters of filter should be changed so as to obtain impedance of the one drive group above the 2,4 Ω. Such value of input impedance of a traction vehicle can be obtained (with assumption that filter capacitance does not undergo changes -C_f= 6,5 mF) by increase of the filter inductance up to L_f = 10mH. While, in order to fulfil the norm in its old version for multiplied traction with two vehicles, one should increase the filter inductance up to 60mH for each filter. It should be noted that above considerations refer to the number of filters for one traction vehicle and the case in which one inverter supplies one traction motor and is equipped with an individual input filter. Analysing the impact of traction vehicle input impedance on the influence of the supply system on windings of the jointless circuit operating with higher harmonics, the 1500 Hz frequency has been considered. The norm does not regulate a minimum value of required impedance for higher frequencies, thus on the basis of filter characteristics (fig. 12) the maximum value of harmonics 1500Hz ($U_{1500max}$), which can appear in the supplying voltage, but which would not cause the excess of harmonics content in traction current should be defined. Knowing the values of filters impedance for frequency 1500Hz and limitations of harmonics content in traction current [1] it can be concluded that with application of a filter with a choker Lf = 10 mH $U_{1500max}$ it should not exceed the value of 164mV, while with application of a choker Lf = 60mH the value of 976 mV. In addition, one should pay attention to the fact that decrease of required minimum input impedance of a vehicle for frequency 50Hz to 0,3 Ω , is limited to 360 mV by the maximum admissible value of harmonic 50Hz in rectified voltage. Taking into account the fact that output filters of a substation do not damp component 50Hz and the possibility of occurrence of the mentioned component in substation output voltage, disturbing influence of a traction substation on track circuits with various types of imperfections of a rectifier set (asymmetry in resistance of rectifier branches) can be expected. Considering similar solutions for individual traction for a 4-motor vehicle, in order to fulfil the new norm it is sufficient to apply chokers L_f = 6 mH , while in order to fulfil the old one it was necessary to use chokers L_f = 28 mH. Characteristics of the filters under discussion are presented in fig. 13. Knowing the values of filters impedance for frequency 1500Hz it can be concluded that with application of a filter with a choker L_f = 6 mH $U_{1500max}$ it should not exceed the value of 196 mV, while with application of a choker L_f = 28mH the value of 924 mV.

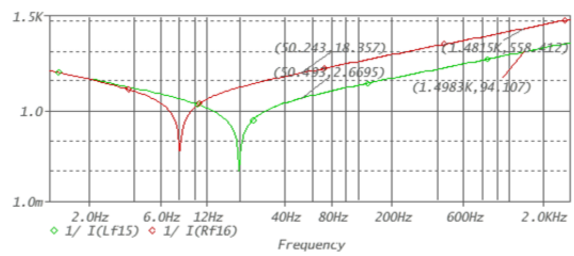


Fig. 12. Characteristics of impedance module of exemplary input filters allowing for the fulfilment of the norm PN-EN 50388 [13] for multiple-operation of a 4-motor vehicle with accordance to the a) effective version (1/I(Lf15) L_f = 10mH), b) previous version (1/I(Lf16) L_f = 60mH)

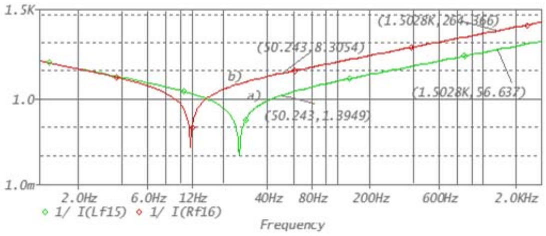


Fig. 13. Characteristics of impedance module of exemplary input filters allowing for the fulfilment of the norm PN-EN 50388 [13] for individual traction of a 4-motor vehicle with accordance to the a) effective version (1/I(Lf15) L_f = 6mH), b) previous version (1/I(Lf16) L_f = 28mH)

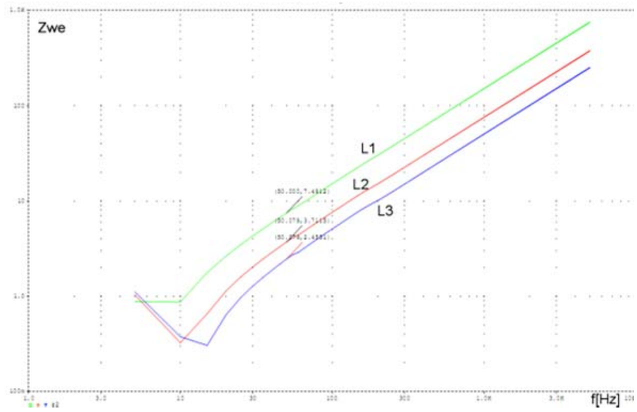


Fig. 14 Exemplary run of module of input impedance of vehicle input filter for different inductance values :L1=24mH, L2=12mH L3=8mH

Systems of train traffic protection, which are exploited by PKP, operate relying on the track circuits, which use rails conducting current for signalling current conduction. Track circuits are commonly used by PKP (of the older type) and operate in the range of various frequencies (of old type 50Hz), while new circuits operate with frequency range 1.2-2.7 Hz. Occurrence of current of higher harmonics in traction current in these bands can cause disturbances in the appropriate operation of these circuits. It especially concerns the frequency band of 1.3-3 kHz with simultaneous occurrence of a disturbances group (asymmetry, lack of substation filter) but also with low frequencies, when occur disturbances in the operation of vehicle circuits and filters in the substation will not operate. Therefore, value of input impedance with consideration of various types of vehicle operation is of high importance

An exemplary run of a module of an input impedance filter of a vehicle in the function of frequency that meets the requirements of not exceeding admissible component values of current higher harmonics is presented in fig. 14 [16,17].

As can be noted, reduction of requirements concerning the input impedance values highly influences the parameters of input filter, which decide about gabarits of L filters chokers and related construction problems occurring with a stock design, especially the one designed for a multiply-operation [8].

Summary

The article presents results of simulating analysis of input impedance of a traction vehicle drive group equipped with an inverter driving system. The influence of input filter parameters, for 5 different solutions has been analysed. The necessity of application of a separate input filter for each driving group and their parallel connection as a part of one vehicle, but also the anticipated connection of vehicles for multiply-operation (very often not used) cause the decrease of input impedance for the whole group of vehicles, which forces application of resize of input filter parameters of individual vehicles. The use of appropriate methods of analyses allowing for the determination of vehicle input impedance at the stage of design, with consideration of the required criteria, enables to shorten the process of insurance of compatibility requirements during acceptance testing of a vehicle.

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