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Active Suppression of Low-frequency Interference Currents by Implementation of the High-performance Control System for the Grid-interfaced Converters

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Operation of traction drive and auxiliary power supply converters installed onboard modern vehicles causes increased content of line harmonics and interharmonic components in the line current. Passive techniques for filtration of low frequency interference line currents appeared to be insufficient, but are combined with active mitigation techniques. The paper describes and suggests active suppression methods based on proper design of the grid interface of the power converter and its corresponding control system. Interference currents, including those induced by the operation of onboard power converters can significantly influence the correct operation of telecommunication, train control systems and other railway signaling infrastructure along the tracks, having direct impact to the safety of the railway transport. Therefore, suppression of low-frequency interference line currents requires careful implementation of active/passive methods. For purpose of quality evaluation of performances of the grid interface of the traction drive converters and its corresponding control system in particular, a series of tests for assessment of the line current frequency spectrum, resulting from the operation of the converter in typical exploitation conditions, were performed. Tests were performed in laboratory conditions and on the vehicle, with satisfactory results.

Key words: Active filter, Control system design, Interference currents suppression, Line-side converters for railway applications

Aktivno potiskivanje nisko-frekvencijskih struja smetnji u pojnoj mreži djelovanjem na upravljačko-regulacijsku strukturu mrežnog sučelja pretvarača. Široka primjena pretvarača glavnih i pomoćnih pogona, na suvremenim željezničkim vozilima, uzrokuje pojavu povećanog sadržaja neželjenih viših harmonika te međuharmonika u strujama pojne mreže. Pasivne tehnike filtriranja nisko-frekvencijskih struja smetnji pokazale su se nedostatnim, te se kombiniraju s aktivnim tehnikama. U radu su predložene aktivne metode potiskivanja zasnovane na odgovarajućem dizajnu mrežnog sučelja pretvarača glavnih i pomoćnih pogona i pripadne upravljačko-regulacijske strukture. Struje smetnji, pa tako i one nastale kao posljedica rada pretvarača glavnih i pomoćnih pogona instaliranih na vozilo, uzrokuju elektromagnetske smetnje koje mogu značajno utjecati na ispravan rad telekomunikacijske (TK) i signalno-sigurnosne (SS) infrastrukture uz prugu, a samim tim i na sigurnost željezničkog prometa. Stoga se potiskivanju nisko-frekvencijskih struja smetnji u pojnoj mreži treba pristupiti s posebnom pozornošću, koristeći pasivne/aktivne mjere. U svrhu ocjene kvalitete postignutih radnih karakteristika mrežnog sučelja pretvarača za napajanje glavnog pogona, u smislu potiskivanja struja smetnji, proveden je čitav niz pokusa mjerenja spektralnog sastava struja pojne mreže pod djelovanjem pretvarača u tipičnim uvjetima eksploatacije. Ispitivanja su provedena u laboratorijskim uvjetima, kao i na vozilu, uz zadovoljavajuće rezultate.

Ključne riječi: aktivni filtri, dizajn regulacijskog sustava, potiskivanje struja smetnji, mrežni pretvarači za željeznička vozila

1 INTRODUCTION

Within the last two decades, dynamic performances of the modern railway vehicles improved drastically, as a result of the wide application of power electronic devices installed onboard – primarily IGBT based traction drive converters, i.e. power converters for the main propulsion, and the auxiliary power supply units. Traction converters supply main propulsion drives based on AC traction motors, while auxiliary power converters units provide power supply for all other systems onboard railway vehicle (ventilation of the traction motors, pumps within the cooling system of the power converters, air compressors, battery chargers...). Application of power electronics onboard modern railway vehicles resulted with many benefits, in-

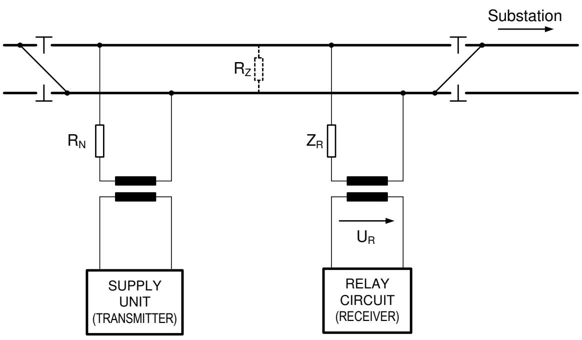


Fig. 1. Simplified schematic of the track circuit for the occupancy control of the double isolated track section with "Z" configuration of insulated joints

cluding improved vehicle dynamics due to installed AC traction drives, outperforming corresponding DC drives by dynamic characteristics as well as by ease and costs of the maintenance, increase of power that can be transferred to the vehicle through the overhead line, possibility of regenerative braking with favorable impact to the total energy consumption of the vehicle and the maintenance of the other, hydraulic or electro-pneumatic brake systems...).

However, operation of power converters installed onboard causes increased content of interference currents – high order harmonics and interharmonic components – in the overhead line current as well as in the return current through the rails and other return paths [1-9].

Low-frequency interference currents and disturbances, especially interharmonic components, are much harder to filter out and therefore are particularly dangerous, if their frequency is equal to or very close to the operating frequency bands of the train control and other railway signaling infrastructure along the tracks.

Interference mechanism between railway vehicle and the track circuit for occupancy control on the double isolated track section, is illustrated by Fig. 1.

A track circuit usually has power applied to each rail and a safety relay coil wired across them. The safety device (relay) and the power supply are attached to opposite ends of the section in order to prevent broken rails from electrically isolating part of the track from the circuit.

When the track section is clear, i.e. when no train is present, the relay is energised by the current flowing from the power source through the rails. Otherwise, when a train is present, its axles short the rails together; cutting out the current to the track relay coil, and it is de-energised. Consequently, circuits through the relay contacts report the clear/occupied status of the track section. A series resistors limit the currents when the track circuit is shunted, i.e. short circuited.

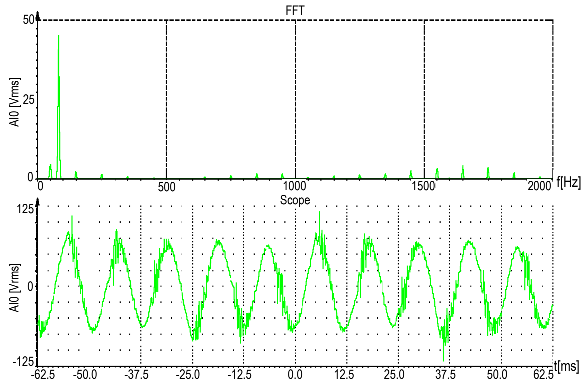


Fig. 2. Waveform of the relay coil voltage U_R, and corresponding FFT spectrum in a frequency range up to 2 kHz, during correct operation of track circuit when the track section is clear: transmitter energizes the receiver by circuit specific operating signal (in this case $83^1/_3$ Hz)

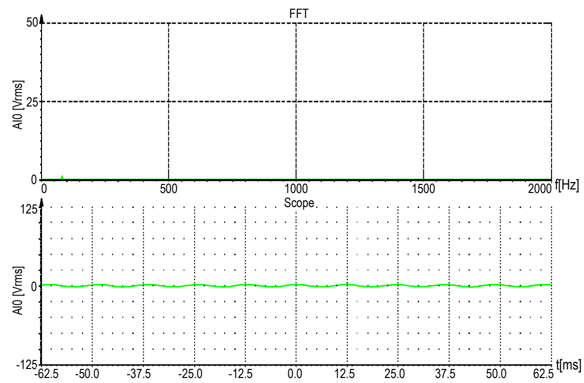


Fig. 3. Waveform of the relay coil voltage U_R, and corresponding FFT spectrum in a frequency range up to 2 kHz, during correct operation of track circuit when the track section is occupied: there is no circuit specific operating signal since the input of the relay device is short circuited by axles of the railway vehicle

Waveform of the relay coil voltage U_R, and corresponding FFT spectrum in a frequency range up to 2 kHz, during correct operation of track circuit, when the track section is clear, is presented in Fig. 2. Transmitter (power supply) energizes the receiver (relay coil) by circuit specific operating signal ($83^1/_3$ Hz).

When the train is present, immediately after it enters the track section, the input of the relay device is short circuited by axles of the railway vehicle (Fig. 3).

Loss of the input signal to the receiver (relay coil) activates the occupied status of the track section.

In case that power converters installed onboard generate sufficient content of the interference currents within the narrow frequency band around the track specific operating frequency, vehicle will continue to energize the receiver, acting as a power supply. Therefore, the train will not be successfully detected, which can cause high proportion severe accidents with potentially enormous hazardous and tragic consequences.

Suppression of interference currents is carried out by implementation of active and passive methods [10-14]. Passive methods include installation of adequate power filters in the input stage of the line-side converters, by considerable increase of stray inductances of the multi-coil transformer windings for traction and auxiliary power supply converters, by installation of properly sized auxiliary filtering windings and AC filters in the output stages (e.g. sinus-filters attached to the outputs from auxiliary power supply units). Active mitigation techniques are performed primarily by appropriate design of the electrical power circuit of the grid-interface of the traction converters and auxiliary power supply units (line-side converters), and the corresponding control system.

Typical electrical power circuit topologies of the grid interfaces of the traction and auxiliary power converters, intended for operation on AC railway networks are presented in the following sections. In order to achieve the most effective way to suppress the line interference currents, particularly low-frequency harmonics, sub-harmonic and interharmonic components of the line current, some issues concerning the design of electrical power circuit of the grid-interfaced converters and accompanying control system are discussed in the paper.

2 ELECTRICAL POWER CIRCUITS OF THE TRACTION DRIVE AND AUXILIARY POWER SUPPLY CONVERTERS

Connection between the overhead line and the line-side converter of the traction drive and auxiliary power supply converters differs with respect to the catenary voltages the railway vehicle is designed for [15-20]. On AC power supply systems (25 kV, 50 Hz; 15 kV, $16^2/_3$ Hz) the traction converter is typically connected to the dedicated windings of the single-phase multi-coil transformer, while on DC networks (750 VDC; 1.5 kVDC; 3 kVDC), standard solution is a direct connection through the input power filter (Fig. 4).

Connection of auxiliary power supply converters to the DC network does not differ from the solution for the traction converters.

Auxiliary power supply converters, intended for operation on AC supply network, are also typically connected to the dedicated secondary winding of the single-phase multi-coil transformer, but there are some solutions were the grid

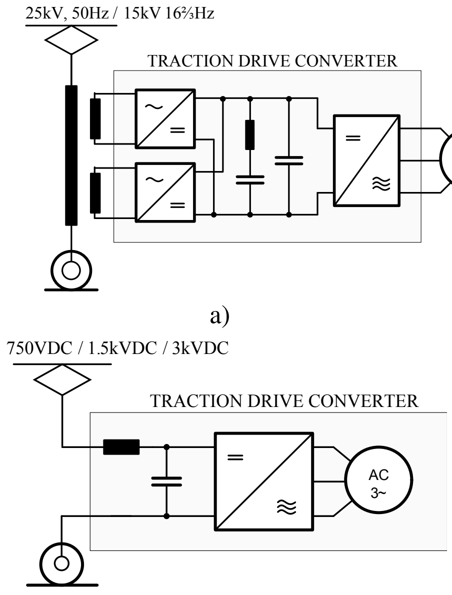


Fig. 4. Grid connection of traction drive converter to: a) AC supply network: 25 kV, 50 Hz *or* 15 kV, $16^2/_3$ Hz*; b) DC supply network:* 750 V, 1.5 kV *or* 3 kV

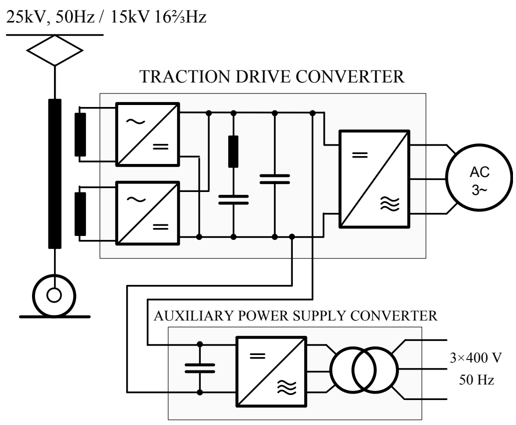


Fig. 5. Auxiliary power supply converter connected to the stabilized DC-link voltage of the traction drive converter

interface of the auxiliary power supply converter is connected directly to the stabilized DC link voltage of the traction drive converter, i.e. at the output of its line-side converter (Fig. 5).

Typical electrical power circuit topology of the traction drive converters intended for operation on AC power supply networks, is a pair of single-phase inverter bridges whose outputs are connected in parallel to the DC-link, together with the main DC-link capacitor, resonant filter and braking/protection unit (Fig. 6).

Such configuration of the line-side converter enables

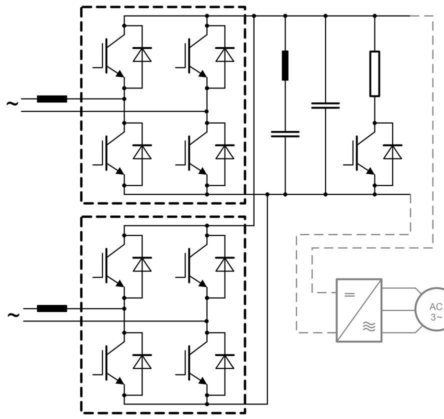


Fig. 6. Typical electrical power circuit topology of the traction drive converters intended for operation on AC power supply networks

Table 1. Values of key parameters of the electrical power circuit of the traction drive converters: f_s - grid frequency, U_{dcN} & P_{dcN} - rated DC-link voltage and rated DC-link power, C_d - main DC-link capacitor, C_2 - resonant filter capacitor

Vehicle	f_s [Hz]	P_{dcN} [MW]	U_{dcN} [V]	C_d [mF]	C_2 [mF]
A	50	0.550	1500	9.6	4.8
B	50	2.150	2800	7.8	3.4
C	50	0.610	900	18.0	3.16
D	50	1.000	1800	10.0	10.0
E	16²/3	3.200	2800	9.0	7.67
F	16²/3	3.200	2600	8.28	7.13
G	16²/3	3.000	2800	10.6	7.0
H	16²/3	2.400	2400	12.0	8.0
I	16²/3	2.000	2800	6.2	4.75

AC electrical traction drive full four-quadrant operation, necessary for application in modern railway vehicles.

Topology with two inverter bridges is used in order to realize high-power units for the main propulsion traction drives (usually over 500kW), when demands on operating electrical characteristics are drastically increasing. Besides, by implementation of interlaced PWM (Pulse-Width Modulation), a resulting switching frequency is twice higher, while retaining the total switching and conduction losses on a similar level. Distribution of power losses on more IGBT switches has favorable impact on the design of the cooling system as well.

Resonant filter connected to the DC-link of the traction converter is tuned to the frequency twice higher than the frequency of the input grid voltage. Thus, for 50 Hz AC supply networks, resonant filter is tuned to the frequency of 100 Hz, in order to damp the oscillations of the DC-link voltage caused by the fundamental component of the line current, after the rectification by the line-side converter. Beside the first resonant frequency, equal to the double grid frequency, there is another resonant frequency, resulting from the combination of the main DC-link capacitor and the aforementioned resonant filter. Thus, a proper selection of parameter values for the resonant filter and main DC-link capacitor is very important.

In fact, harmonic components of the line current caused by counter-voltages generated by line-side converters, related to the second resonant frequency can generate dangerous low-frequency interharmonic components of the line current [21]. Based on the hardly available data about the key values of the electrical power circuits of the line-side converters of the traction drives, small overview of those parameters for several vehicle types is made (Table 1).

Control system of the output stage of the traction drive converter, i.e. three-phase inverter bridge, is designed to achieve the best performance regarding the dynamic characteristics of the AC traction drive, employing asynchronous traction motor and a variation of field oriented control (FOC), or direct torque control (DTC) algorithms, [22-34].

Due to the hysteresis character of the DTC algorithm, traction drives with direct torque control generate a broad noise spectrum of current harmonics, that can be injected in the DC link of the converter. Injected harmonics can cause a generation of significant content of the low-frequency disturbances in the line current, by their interaction with the fundamental component of the line current and the control system of the line-side converters.

Standard topology of the grid interface of the auxiliary power supply converters, powered from AC network, is configuration of several parallel/series connected boost converters, according to the demanded power ratings and the input voltage range.

Parallel configurations of auxiliary converter (Fig. 7) are usual at lower input voltage ranges, while series configurations are typical for higher input voltage ranges.

The boost converter, i.e. grid-interface of the auxiliary converter, acting as an active rectifier, also stabilizes the output DC-link voltage, while maintaining nearly constant voltage regardless of line voltage variations, including both fluctuations and distortions. The output modules of the auxiliary power supply converter (three-phase inverter units with fixed/variable frequency outputs, battery chargers, etc.) are then connected to this stabilized DC-link voltage in order to supply various loads onboard (variable/fixed frequency AC drives, lighting, information system, etc.). The boost converter is required to operate, from no-load to full power, over a wide AC input voltage range, produce a stabilized output DC-link voltage, and support full output load drop.

Some design considerations regarding the configuration of electrical power structure of the grid-interface of the auxiliary power supply converter are discussed in [35].

3 LOW-FREQUENCY INTERFERENCE LINE-CURRENT MITIGATION TECHNIQUES

Injection of interference line currents in the power supply network, due to the operation of traction drive and auxiliary power supply converters, are primarily caused by interaction between the control structure of the corresponding line-side converter and:

- disturbances generated by output stages of the converters, (high performance AC traction drives based on induction motor and FOC/DTC control, inverters in combination with transformer for galvanic isolation of loads...)
- current-voltage circumstances in the power supply system(interaction with other vehicles, powered from the same substation, direct interaction with the infrastructure of different substations, quality of the contact between the catenary line and the pantograph. . .).

Methods for mitigation of interference line-currents are basically derived based from passive/active approach.

Passive mitigation techniques include:

- installation of power filter at the input of the line-side converter (high voltage L-C filters, filter windings, increase of stray reactance of transformer. . .)
- installation of filters in the output stages, particularly the outputs of auxiliary converters (various configurations of *sinus filters*. . .)

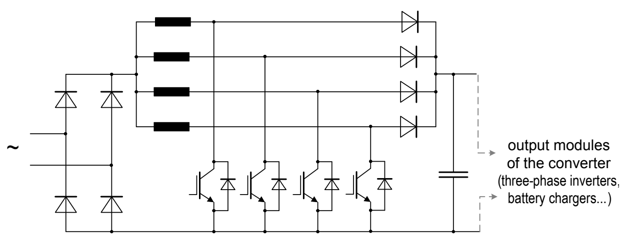


Fig. 7. Typical configuration of electrical power circuit of the grid interface of the auxiliary power converter, powered from AC power supply systems, for low input voltage range, and high rated power

- suppression of DC current component in sections of the converter with combination of inverters and isolation transformers (in order to prevent the distortion of the load currents due to the saturation of the magnetic core [36]).

Active mitigation techniques [37-46] comprise:

- selection of the proper modulation scheme/strategy and its adequate implementation (type of modulation. . .)
- algorithms for elimination of effects of non-linearities in the control of IGBT switches (*dead-time elimination. . .*)
- implementation of appropriately designed control system (feedback signal processing, implementation of model referenced predictive control algorithms, and maximal usage of feed-forward control schemes. . .).

Among the passive measures, installation of sinus filter in the output stages of the auxiliary power supply converters is regularly applied, in order to obtain nearly sinusoidal output voltages and load currents from the modulated DC voltage. Sinus filters are used to overcome the numerous problems associated with long cable runs between an inverter drive and a motor, by reducing the voltage rise rate *dV/dt*, and associated peak voltages and currents, to a benign level. The asymmetric voltage and current waveforms produced by pulse width modulation, are converted back almost to a pure sine wave, which helps to reduce RFI and often removes the need for a screened cable. There are also motor noise, temperature and mechanical stress reduction benefits from using a sinusoidal filter.

There are many variations in the implementation of the sinus filter. More detailed overview of implementations and possible connections of sinus filter with the transformer and inverter is given in [47-50]. Based on practical experience, a version of sinus filter utilizing the stray inductance of the transformer as a filter inductance, so that the filter capacitors are directly attached to the secondary windings (Fig. 8), proved to be *state-of-the-art solution*, and is most widely used in practice.

Transformer as a part of the sinus filter, also serves for galvanic isolation of loads from the input, requires very careful design of the control system of the converter. Actually, improper control of the converter can result with the DC component of the output current, which could cause a saturation of transformers magnetic core and load current distortion. Thus, load current distortion, reflected as a DC link voltage disturbance, could initiate generation of interference line currents, as a consequence of the operation of the line-side converter and its control system.

Both, passive and active approach, are used in order to eliminate the DC component of the magnetization current. Passive methods (application of additional series resistor between the inverter and transformer, bigger air-gap...), are easier to implement, without any changes in control system, but result as larger, less efficient and more expensive solutions, with respect to the ones obtained by application of active methods (elimination of dead-time effects in control of IGBTs, detection and compensation of the DC component in the output voltage of the inverter, detection of core saturation...).

Since the weight of equipment installed onboard is always important issue in vehicle design, active approach in elimination of the DC component of the magnetization current is obviously much more acceptable.

Active techniques for suppression of the DC component of the magnetization current [42-44] modify the control pulses to IGBTs in order to minimize the negative effects of nonlinearities in the control of semiconductor switches, or alter the current reference waveform of the inverter, in case that DC component of the magnetization current, or the current distortion due to core saturation is detected.

The negative impact of the dead-time effect on the control of the IGBT switches can be drastically reduced by several changes in the control system, employing the output current feedback control. These algorithms can be implemented on dedicated hardware platform, while the rest of them can be integrated in the control structure realized in the digital signal processor (DSP). The core of the PWM unit is mostly embedded also in the DSP, or in some cases in the accompanying FPGA chip [45,46].

Beside the aforementioned problems with elimination of the DC component of the magnetization current, there are many other issues related to the line-current harmonics emerging as a result of the operation of parallel/series connected line-side converters of traction drives and auxiliary power supply converters. Due to harmonic intermodulation between the converters, including the fundamental component of the line current, resulting content of low-frequency interference currents can be significantly increased. On the other hand, set of equal, coherently controlled traction drive and auxiliary power supply converters enables additional options for the suppression of low-frequency interference currents with respect to the overhead line power supply system. Problems related to the mutual interaction of several vehicles powered from the same substation, including the possible impact of such interactions on stability of the power network is another class of problems.

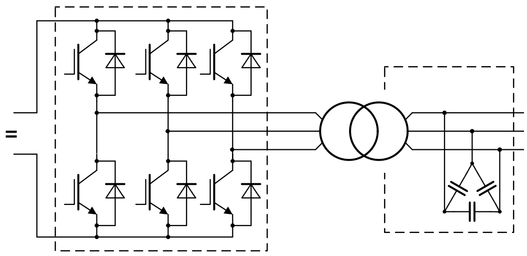


Fig. 8. State-of-the-art solution of sinus filter, utilizing the stray inductance of the transformer as a filter inductance

Nevertheless, for successful implementation of the active mitigation techniques for suppression of the low-frequency interference line currents, in depth knowledge of the modulation techniques, solutions for compensation of imperfections in the control of IGBT switch is required.

4 CONTROL OF THE CONVERTER

In order to achieve the best dynamic performances, flexible control of output currents and voltages retaining their size and mass as small as possible, i.e. high specific power density, almost all power converters installed onboard modern railway vehicles are operating in switching mode.

Change of the amplitude and frequency of the output voltage is done by application of various switching sequences to the IGBT switches, i.e. modulation [51-58].

Fundamental frequency of the generated voltage is for all grid-interfaced converters powered from AC network, including line-side converters of the AC traction drives and auxiliary power supply converters, tied to the grid frequency. Counter-voltage generated by the line-side converter is non-sinusoidal, containing wide spectrum of harmonic components besides the fundamental. High-order line harmonics are sinusoidal voltages whose frequency is an integer multiple of the grid frequency. Average value of the output voltage in specific time interval represents the DC component of the voltage in that time frame. If the basic time frame is set to the period of the switching frequency, averaged sinusoidal waveform of the fundamental voltage component is obtained.

The very existence of other harmonics in the generated counter voltage, together with the mechanism of the intermodulation with the fundamental component of the grid voltage and other already injected harmonics, opens up the possibility for generation of lots of problems related to the electromagnetic compatibility issues, including not only the problems of possible negative mutual impact of converters and other equipment installed onboard, but also the problems regarding the interference line currents and the possible negative effect on the correct operation of telecommunication and train control systems and other railway signaling infrastructure along the tracks.

Selection and implementation of the proper modulation scheme can significantly reduce the risks and problems related to the harmonics content generated by the operation of traction drive and auxiliary power supply converters. Hence, the requirements set on the modulation algorithm include generation of maximal amplitude of the fundamental voltage, and the best frequency spectrum possible, as well as very good dynamic characteristics with respect to the versatile voltage and load variations, at moderate IGBT switching frequency (in the applications for line-side converter of the traction drive and auxiliary power supply units – 500 Hz. . . 4kHz).

Additional requirements on modulation scheme for AC converters include true grid synchronous operation with phase-control of the switching frequency harmonics, in order to interlace all converters onboard, and topology specific requirements related to the parallel/series configurations of the line-side converters for traction drives and auxiliary power supply converters).

Carrier based pulse-width modulation is typical for single-phase grid-interfaced traction drives and auxiliary power supply converters, while the most often used subversion of that modulation scheme in this applications is synchronous, sinusoidal, unipolar PWM:

- synchronous (ratio between the switching frequency and the grid frequency is an integer value)
- sinusoidal (with respect to the modulation index over grid voltage period, i.e. modulation signal is sinusoidal)
- unipolar (with respect to the generation of output voltage, i.e. output voltage waveform)
- symmetric/asymmetric (regarding the modulation index update instances, i.e. whether it is sampled once/twice during modulation carrier interval, respectively).

To achieve about the same harmonic spectrum of the line currents, significantly higher switching frequency is required in case that asynchronous modulation is applied, instead of the synchronous modulation. Consequently, asynchronous modulation would cause considerable drop of efficiency, due to higher switching frequency, and much higher level of electromagnetic interference in very wide frequency range. Therefore, it is unacceptable in line-side converters applications for traction drives and auxiliary power supply converters.

Railway vehicles powered from AC power supply, grid-interfaces of the traction drive and auxiliary power supply converters are connected to the overhead line by means of multi-winding single-phase transformer. Regarding high performance demands on these converters and their dynamic characteristics, in order to obtain the best possible line-current spectrum and current reference tracking, synchronous, sinusoidal, unipolar PWM with line current closed control loop.

5 CONTROL SYSTEM STRUCTURES

To achieve the best dynamic characteristics of the line-current control loop, the current controller is supported by a model-referenced feed-forward control path, whose output signal is formed according to the actual values of the control variables (voltage and current reference, state-variables...). Besides, for DC-link voltage control purpose, an outer voltage control loop is added to the control system. Amplitude of the current reference waveform is formed according to the output from the superimposed voltage controller. Typical parallel configuration of the electrical power circuit of the grid-interface of the auxiliary power supply converter and the simplified block diagram of the corresponding control structure are given by Fig. 9. Parallel configuration of several boost converters is typically applied in case when relatively high power output at rather low input voltage range is demanded by application. In order to minimize the harmonic content at the switching frequency, control PWM pulses of all parallel connected boost converters are interlaced, i.e. phase-shifted by 90°el., resulting in the higher effective switching frequency with respect to the power supply grid [51].

For synchronization of the current reference to the line voltage purpose, an actual value of the phase-angle of the grid voltage is needed. Since the phase angle cannot be measured directly, it must be evaluated indirectly, by some of the estimation techniques. There are many algorithms for the phase-angle estimation of the line voltage. More detailed overview of phase-angle estimation techniques, employed in grid-interfaced converter applications is given in [59-70]. Actual value of the line voltage and its frequency are very often additional outputs from the estimation algorithm.

Simplified block diagram of one particular algorithm for the phase-angle estimation of the line voltage, the modified EPLL (*Enhanced Phase Locked Loop*) algorithm is given by Fig. 10.

Modified EPLL algorithm differs, from the original version, by implementation of SDFT (*Sliding Discrete Fourier Transform*) filter in the input section of the phase-detector, and modification of the loop filter (adaptive sliding mean value filter, self-tuned to the double line voltage frequency) in the output path for the estimated frequency ω and phase-angle θ, efficiently eliminating odd harmonics from the estimated outputs (formerly the main drawback of the original EPLL), while preserving good dynamic characteristics.

Implementation of SDFT filter to the line voltage signal, i.e. the input section of the phase detector, and notch filter in the output stage, drastically improves the robustness while retaining the dynamic performance, even in the very polluted grid environment, i.e. highly distorted line voltage, significant content of line harmonics and interharmonics, sags and phase jumps of the line voltage, even multiple zero-crossings of the line voltage within the fundamental period, Fig. 11.

Beside the variations of the EPLL algorithm, phase-angle estimation employ multiple ANF filters (Adaptive Notch Filter), i.e. a combination of narrow-band adaptive filters, whose central frequencies are matched to the fundamental line frequency and its multiples (Fig. 12).

The ratio of total power of all traction drives installed onboard railway vehicle to that of the auxiliary power supply converters is more than 5:1. For instance, a train with two traction drives and one auxiliary power supply unit per powerhead, has a typical ratio between traction and auxiliary converters of 2000kW to 200kW in favor of traction drives. At the same time, the IGBT switching frequencies are much lower in traction drive converters than in auxiliary power supply converters, typically a few times. Thus, traction drive converters performances, with

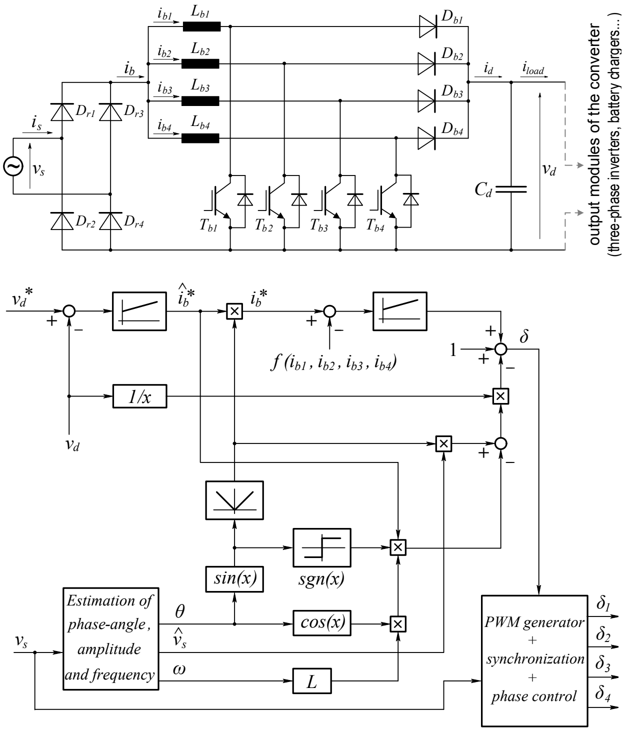


Fig. 9. Control structure for the typical configuration of the electrical power circuit of the grid-interface of the auxiliary power supply converters powered from AC supply network

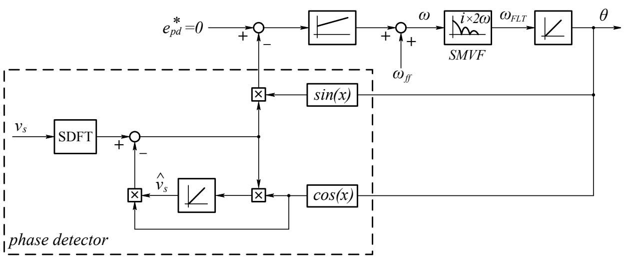


Fig. 10. Simplified block diagram of particular algorithm for the phase-angle estimation of the line voltage, the modified EPLL (Enhanced Phase Locked Loop)

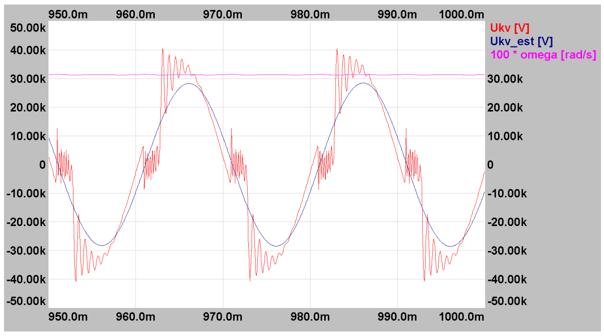


Fig. 11. Output waveforms from the modified EPLL algorithm for the estimation of the phase-angle, amplitude and frequency of the line voltage, in case of very polluted grid environment

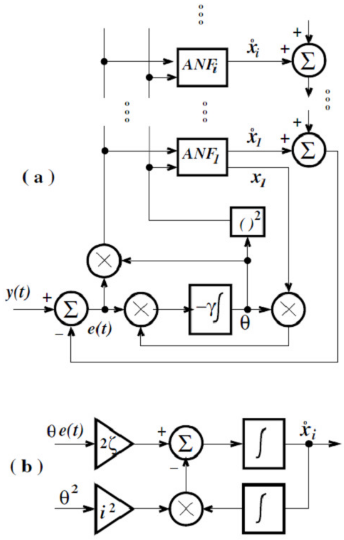


Fig. 12. Adaptive notch filter - ANF: a) simplified block diagram of the multiple ANF filter; b) schematic diagram of the basic ANF filter block (for i^{th} harmonic)

respect to the generation of low-frequency interference line currents, require even more demanding design approach. Grid-interface of the traction drive converters, powered from AC supply system, supports full four-quadrant operation, thus increasing the possibility to generate interference line currents, injected by the output three-phase inverter and motor. For instance, if the output inverter injects harmonic component at 125 Hz into the DC link voltage, it will result in 75 Hz and 175 Hz harmonic components, by means of intermodulation with the fundamental of the line current. Reflected harmonics can fall within the operating frequency range of particular railway safety critical systems. Thus, by selection of the proper modulation type and design of the control system for the grid interface of the traction drive converter, extremely cautious approach is required.

In order to obtain the best frequency spectrum of the line current, a synchronous, sinusoidal unipolar PWM is typically employed in grid-interface applications for traction drives. Control system structure for the grid interface of the traction drive converter powered from AC supply system, based on banks of PIR current controllers (Proportional + Integral-Resonant) is given by Fig. 13.

Estimation of the grid voltage parameters (phase-angle, amplitude and frequency) is realized through, already described, modified EPLL algorithm (Fig. 10), while the estimation of the input voltage to the line-side converter is done by compensation of the voltage drop across the leakage reactance of the dedicated windings of the single-phase multi-coil transformer.

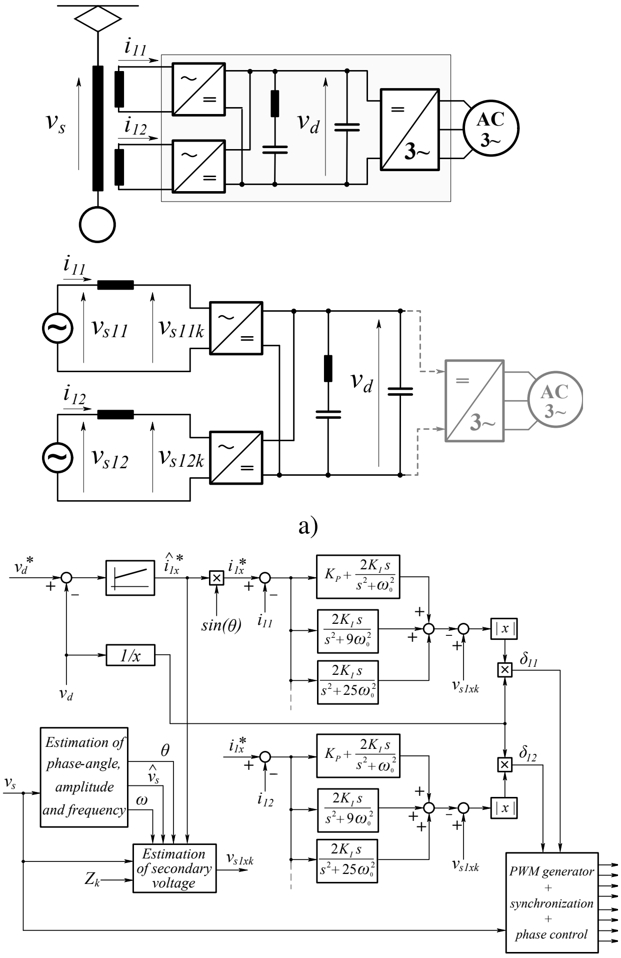
Due to PIR controllers, the control system is characterized by excellent dynamic performance, while maintaining very good harmonic suppression qualities (Fig. 14).

System loop gain, provided by ideal form of the resonant part of the PIR controller, is infinite at the tuned frequency, set to the frequency of supply grid (Fig. 15), thus eliminating any steady state error at that frequency.

Due to its narrow-band action, PIR current controllers inherently enable suppression of all harmonic components of the line current other than the grid fundamental.

Practical implementations include slight damping of the controllers step response (up to several percents), in order to improve stability of the PIR controller and its robustness with respect to the quality and precision of the measurement/estimation of the grid frequency, necessary for real-time recalculation of the coefficients for all employed resonant parts.

Frequency characteristics of the non-ideal resonant part of the PIR controller, tuned to the fundamental grid frequency is given by (Fig. 16), while the characteristics of other resonant parts of the PIR controller look basically the same, except the difference in corresponding central frequencies.



a) b)

Fig. 13. a) Electrical power circuit of the grid interface of the traction drive converter, powered from AC supply system. b) Simplified block diagram of the control system applied to the grid interface of the traction drive converter, powered from AC supply system

Estimation of the input voltage to the line-side converter, by compensation of the voltage drop across the leakage reactance, is needed for evaluation of the feed-forward path output signal, calculated according to the actual value of the overhead line voltage, transformer parameters and the actual value of the current reference. Instead of the regularly sampled actual value of the overhead line voltage, its approximation by the sum of the first few line harmonics is used in some implementations.

The possibility of the phase-control of the PWM carrier, with respect to the zero-crossing of the line voltage, i.e. net-mark, is not explicitly specified in the block diagram of the control system, as it is the integral part of the PWM unit. By coordination of grid interfaces of all traction drive and auxiliary power supply converters installed onboard,

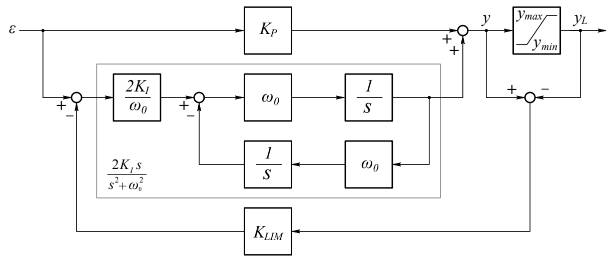


Fig. 14. Block diagram of the PIR controller with anti-windup protection, by active monitoring of the limitation of the controller output against the defined limits. Resonant part of the controller, tuned to the fundamental frequency of the grid ($f_0 = 50$ Hz, $\omega_0 = 2\pi f_0 \approx 314$ rad/s), is additionally marked

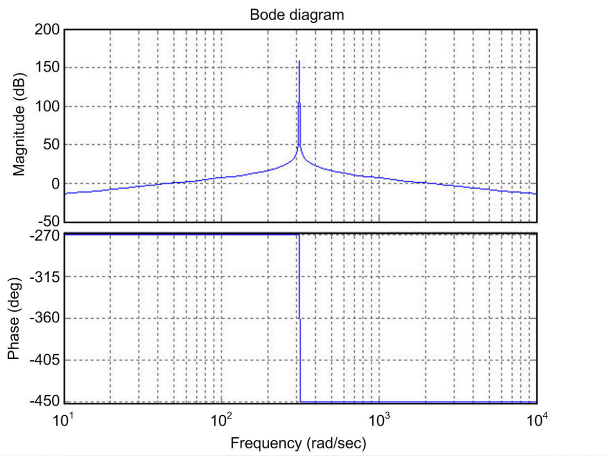


Fig. 15. Frequency characteristics of the resonant part of the ideal form of the PIR controller ($f_0 = 50$ Hz)

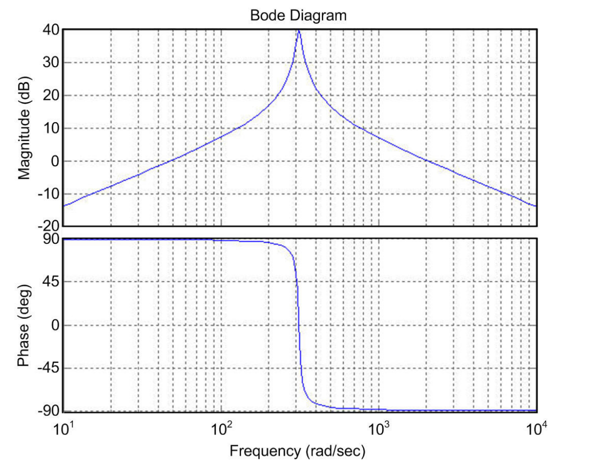


Fig. 16. Frequency characteristics of the non-ideal resonant part of the PIR controller ($f_0 = 50$ Hz, $K_I = 100$)

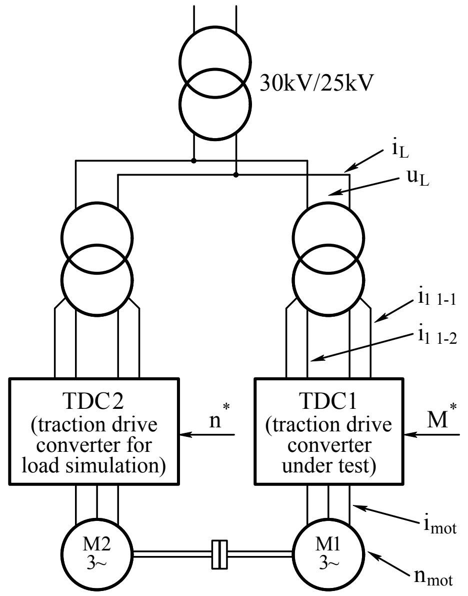


Fig. 17. Simplified schematic of the electrical power circuit of the laboratory test bed for the traction drive converters by using the opposition of two converters, i.e. back-to-back method

switching harmonics can be suppressed even more effectively. Thus, two parallel connected single-phase bridges of the single traction drive grid interface, with interlaced PWM control at 2 kHz, generate resulting switching harmonic of the line current at the frequency of 4 kHz. By interlacing the two traction drives, connected to the dedicated windings of the same multi-coil transformer within the same power-head, switching harmonics can be suppressed even farther in the frequency band around 8 kHz. Accordingly, the phase coordination between the two power-heads of the vehicle can be implemented, in order to push the resulting switching frequency of the overhead line current to the 16 kHz band.

6 QUALITY VALIDATION OF THE CONTROL SYSTEM

For purpose of quality evaluation of performances of the grid interface of the traction drive converters and its corresponding control system in particular, a series of tests for assessment of the line current frequency spectrum, resulting from the operation of the converter, has to be performed. Tests are performed in laboratory conditions, typically employing the opposition of two converters, i.e. back-to-back method, to simulate realistic operating conditions (Fig. 17), as well as by tests performed on the vehicle.

During simulated driving cycle, tested drive is operated directly according to the set torque reference, while the drive for load simulation is configured to operate in speed

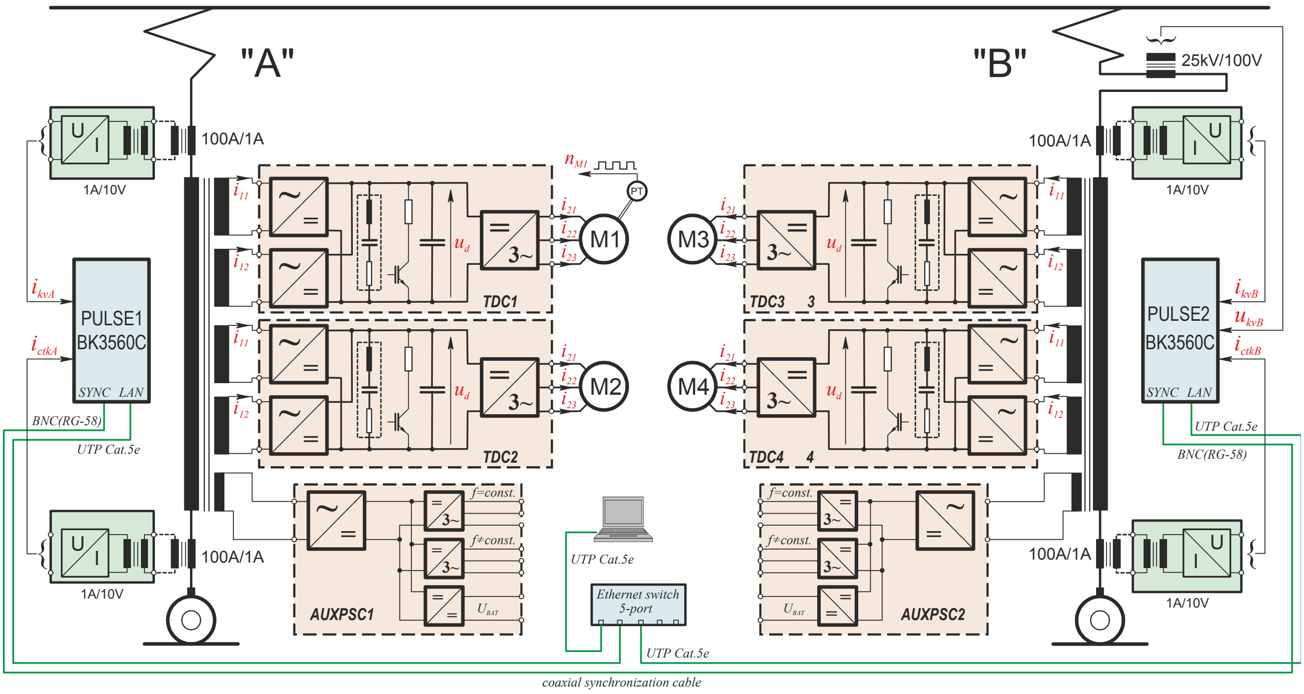


Fig. 18. Typical test configuration for the measurement of the line interference currents, generated by the operation of all traction drive converters (TDC1...TDC4), and auxiliary power supply converters (AUXPSC1, AUXPSC2) installed onboard, based on the two network-connected and synchronized data acquisition systems

control mode, driven by predefined speed trajectory. During the run-up period, drive under test operates in motoring mode consuming energy from the grid, while the drive for the load simulation works in regenerating regime, returning the energy back to the supply grid, and vice versa. If considered in total, energy balance reveals that grid supplies only the energy necessary to cover the internal losses of the test-bed equipment (converters, motors and transformers). Laboratory tests of the traction drive converters alone are not sufficient, with respect to the line interference currents characterization, because of the impact of the torque control and torque ripple characteristics of the drive simulating the realistic load conditions.

More accurate evaluation of performances of the grid interface of the traction drive converters and its control system in particular, is done according to the test results obtained by tests performed directly on railway vehicle. Typically, test configuration should provide simultaneous measurements of all relevant signals in both power-heads (line currents and voltages of all converters installed onboard, traction motor speeds and currents...) by two synchronized data acquisition systems (Fig. 18).

During the performance tests of implemented control structures, presented in the paper, overhead line and return currents were measured for various electrical drive configurations and operating conditions. Preliminary analysis was performed in frequency domain (FFT analysis with predefined FFT resolution, window function, window width and window overlapping...).

Final validation of the impact of the vehicle on supply grid was performed by time domain analysis, applying a set of high-order narrow-band filters on the measured overhead line current. Employed narrow-band filters have predefined pass-band width, order and the prototype of the filter (usually Butterworth). The filtered signal is than averaged with predefined integration base, i.e. width of the time-window, and window overlapping.

Central frequencies of these predefined band-pass filters are set to the typical operating frequencies of the train control systems and other railway safety related devices and track circuits (75 Hz, 83 Hz...). Averaged low-frequency line interference currents, i.e. averaged output from the filters are checked than against the current limits for particular operating frequency band, and must not exceed the allowed values in order to comply to the specifications of particular railway operator.

The effects of the proposed strategy for active suppression of the interference line currents is illustrated by comparison of typical FFT spectrums of the overhead-line current and the phase-current of the traction motor, measured on the vehicle during the start-up (Fig. 19).

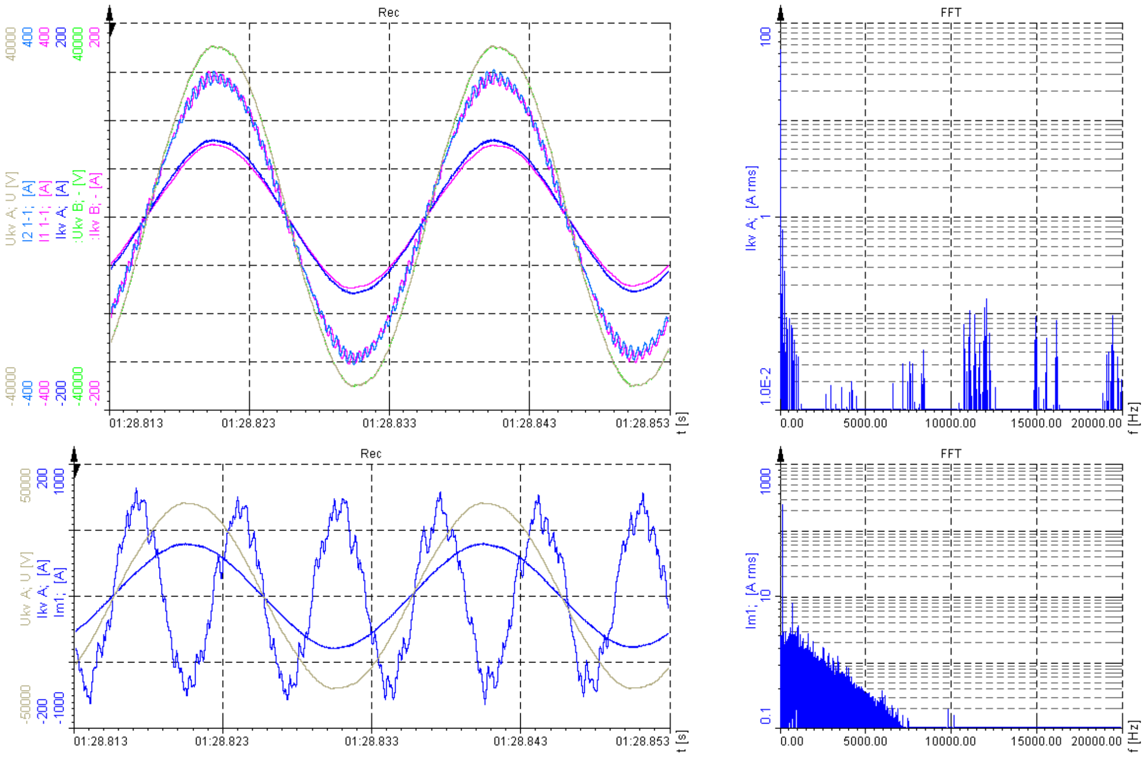


Fig. 19. Typical waveforms of the overhead-line voltages (u_{kvA}, u_{kvB}) and currents (i_{kvA}, i_{kvB}), input currents to the traction drive converters (TDC1, TDC2), traction motor phase current (i_{m1}), and corresponding FFT spectrums, measured during the start-up off the vehicle

7 CONCLUSION

Operation of traction drive and auxiliary power supply converters installed onboard modern vehicles caused increased content of line harmonics and inter-harmonic components in the line current. The correct operation of the automatic train control systems, other safety related track circuits, as well as the telecommunication infrastructure along the tracks, could be severely compromised by low-frequency interference line currents, resulting in direct threat to the safety of railway traffic if the line current harmonic content exceeds permissible levels for the operating frequency bands of safety and telecomm devices. Passive techniques for filtration of low frequency interference line currents appeared to be insufficient, due to the significant increase of the total power of traction drive and auxiliary power supply converters installed onboard, but are combined with active mitigation techniques. Active suppression methods are based on proper design of the grid interface of the power converter and its corresponding control system. Embedded systems based on the high-performance DSP processors, enabled implementation of very complex algorithms and related digital PWM generators, including interlaced operation of PWM units within dislocated traction drive and auxiliary power supply converters, based on accurate estimation of grid voltage parameters, i.e. without any additional synchronization infrastructure.

Major effects of application of the active techniques for suppression of low-frequency interference line currents, are obtained on the single converter level. However, by interlaced operation of grid interfaces of all the converters installed onboard railway vehicle, additional possibility for the suppression of line harmonics, particularly harmonics at the common switching frequency, is enabled.

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