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Wojciech Mazur
Waldemar Zając-Domański
pezajac@cyf.kr.edu.pl
Faculty od Electronical Engineering, Cracow University of Technology

High-frequency cascade converter for a dual-system locomotive

Konwerter kaskadowy wysokiej częstotliwości dla lokomotywy dwusystemowej

Abstract

This article presents the concept for using an LLC resonant converter equipped with a medium-frequency transformer to upgrade the existing EU 07 locomotive into a dual-system vehicle. The work was created which sets out the specification for such an upgrade, but the design was eventually rejected by the investor and it became the subject of a diploma thesis.

Keywords: LLC resonant converter, equipped with medium frequency, modernizing transformer

Streszczenie

W artykule przedstawiono koncepcję wykorzystania konwertera rezonansowego LLC wyposażonego w częstotliwość średnią transformatora modernizującego istniejącej lokomotywy EU 07 do pojazdu dwusystemowego. Praca określa specyfikację takiego ulepszenia, ale projekt został ostatecznie odrzucony przez inwestora i stał się przedmiotem pracy dyplomowej.

Słowa kluczowe: konwerter rezonansowy LLC, wyposażony w częstotliwość średnią, transformator modernizujący

1. Introduction

The development of semiconductor components, such as in particular isolated gate bipolar transistors, also known as IGBT, having the capacity to operate at voltages of up to 6.5 kV and frequencies in the range of 1 to 10 kHz, has enabled medium-frequency transformers (MFT) to be used in the main circuits of electrically powered locomotives supplied by 15 kV AC systems. One of the major downsides of overhead traction power supply was the need for a heavy transformer, due to the frequency of 16.7 Hz.

The design of a traction converter built with the aid of a medium-frequency transformer (MFT) has been attracting a growing interest thanks to the competitive edge that it offers, compared with systems equipped with heavy and relatively inefficient transformers operating at the power grid frequency. The proposed converter, thanks to its multiplied frequency, is characterized by a reduced size and weight as well as improved efficiency [1, 2].

A medium-frequency transformer is an integral part of an LLC resonant converter. It is designed in such a way that the leakage and magnetizing inductance of the winding are involved in resonance action, which is the reason for the double "L" in the name. The idea of the converter under discussion is based on modularity. Each module has an identical topology, allowing every vehicle to be equipped, for example, with an additional module which would normally be out of service but could be nevertheless switched on in the case of the other's failure or maintenance [4]. The modules on the alternating voltage side, where the fast switch and input choke are found, are connected in series and their number depends on the supply voltage of a given system and the blocking capability of semi-conductor components, such as IGBT transistors, as mentioned earlier on. On the rectified voltage side, the modules are connected in parallel [2].

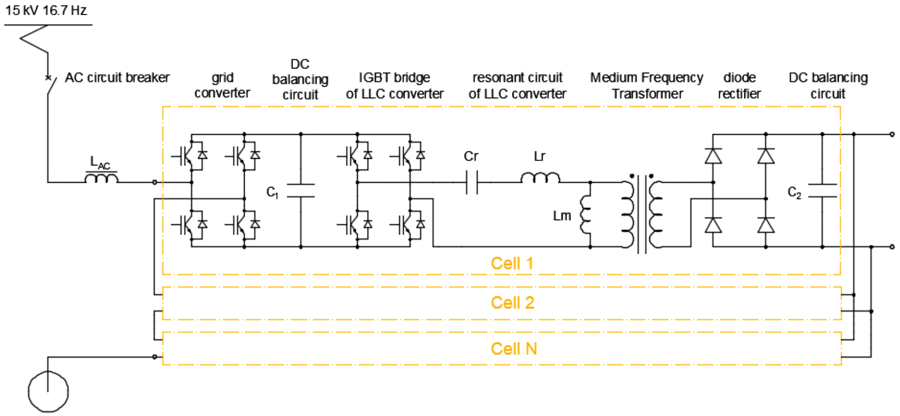


Fig. 1. Converter topology

In each cell presented in the Fig. 1, it is possible to distinguish:

- a four-quadrant grid converter, whose input terminals are connected in series with the terminals of a converter in the subsequent module,

- a DC balancing circuit,
- an LLC resonant converter, which operates in such a way as to prevent energy from returning to the traction grid, consisting of: an IGBT transistor bridge, a capacitor selected for the assumed resonant frequency, a MFT whose leakage inductance forms a resonant circuit in conjunction with the capacitor as well as a diode rectifier whose output terminals are connected to a DC balancing circuit common for all the cells.

2. Multi-level grid converter

A multi-level cascade converter is one of the most frequently used topologies in medium-voltage drives. It is composed of multiply connected single-phase bridges (Fig. 2) which are connected in series on one side to provide the required voltage level and reduce higher harmonics [3].

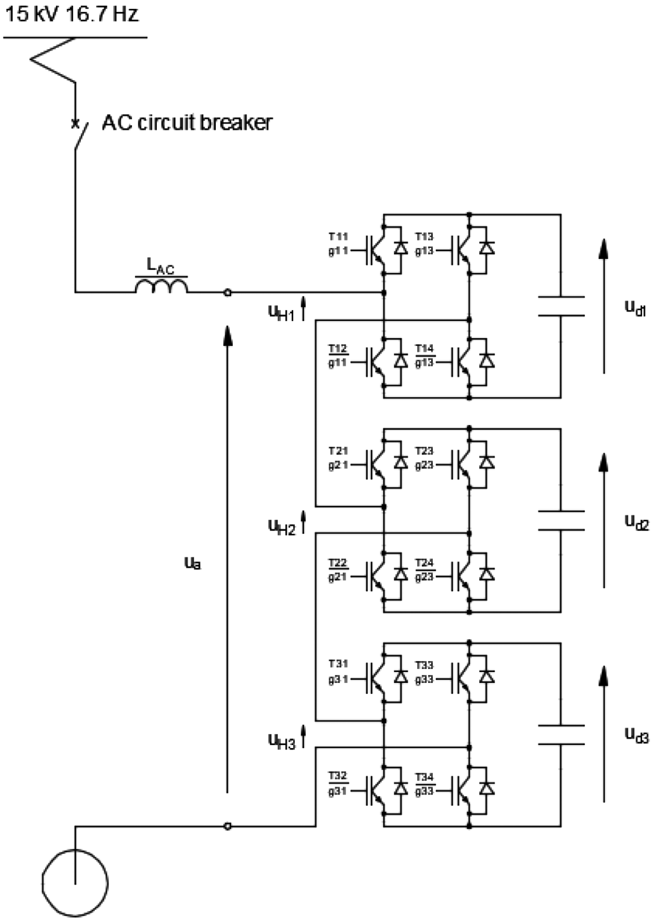


Fig. 2. The example of a seven-level grid converter with a design based on H-bridges

It is possible to generally classify methods of multi-level converter modulation into two categories: phase-shifted and level-shifted modulation. Both of them are applied in cascade converters [3].

A multi-level converter with m voltage levels requires (m-1) triangle waveforms to generate gating signals. In phase-shifted carrier signal modulation, all triangle waveforms have the same frequency and amplitude, while the shift between the adjacent waveforms can be calculated as follows:

$$\theta = 360°/(m - 1) \tag{1}$$

The modulating signal for a single phase is a sinusoid, while gating signals are triggered by a comparison of the modulating waveform u_s with triangle carrier waveforms u_{cr11} to u_{cr33}.

Fig. 3 presents the principle of phase-shifted carrier signal modulation for a seven-level cascade converter, whereby each of the 6 triangle waveforms is shifted by 60 degrees relative to the adjacent waveform. The frequency ratio of carrier wave to modulating wave is $m_f = f_{cr}/f_s = 3$, and the depth of modulation can be expressed as the amplitude ratio of modulating wave to carrier wave, i.e. $m_a = U_s/U_{cr} = 0.9$. The waveforms u_{cr11}, u_{cr21}, u_{cr31} (marked with solid lines) are used to generate gating signals for the upper valves of the left branch of each constituent bridge – T_{11}, T_{21}, T_{31}. The other waveforms: u_{cr13}, u_{cr23}, u_{cr33} (marked with intermittent lines), which are shifted each by 180 degrees relative to u_{cr11}, u_{cr21}, u_{cr31} serve to generate gating signals for the upper valves of the right branch of each constituent bridge – T_{13}, T_{23}, T_{33}. Not all signals for the lower bridges of the valves have been presented, because they operate in reverse to their corresponding upper valves. For example, the gating signal g_{31} for valve T_{31} is formed through a comparison of signal u_{cr31} against modulating signal u_s, whereas the gating signal g_{32} for valve T_{32} in the same branch is formed by negating signal g_{31}.

The instantaneous value of phase voltage may be expressed as the sum of instantaneous voltages for each separate bridge:

$$u_a(t) = u_{H1}(t) + u_{H2}(t) + u_{H3}(t) \tag{2}$$

where:

u_{H1}, u_{H2} and u_{H3} – the partial bridge voltages.

With the application of unipolar modulation, the voltage of each bridge may assume one of three values: $+U_d$, $-U_d$ or 0. A combination of three three–level bridges will produce a seven–level system, while the entire system's phase voltage will reach the following values: $+3U_d$, $+2U_d$, $+U_d$, 0, $-U_d$, $-2U_d$, $-3U_d$, as indicated in the figure below for the last waveform. As valves in different bridges are not operated simultaneously, the rise of phase voltage over time is only U_d, resulting in a considerable decrease in the rate of voltage rise dv/dt and reduction of electromagnetic interferences. Additionally, the combined switching frequency of the converter is related to the switching frequency of a single valve in a manner illustrated below:

$$f_{conv} = (m - 1) * f_{val} \tag{3}$$

where:

f_{conv} – converter switching frequency,

f_{val} – valve switching frequency,

m – number of levels.

This desirable feature means an increase in the converter's switching frequency accompanied by a relatively low switching frequency of individual valves and a shift of harmonics towards higher orders. Another benefit is the reduced switching losses related to a comparably low switching frequency of the valves [3].

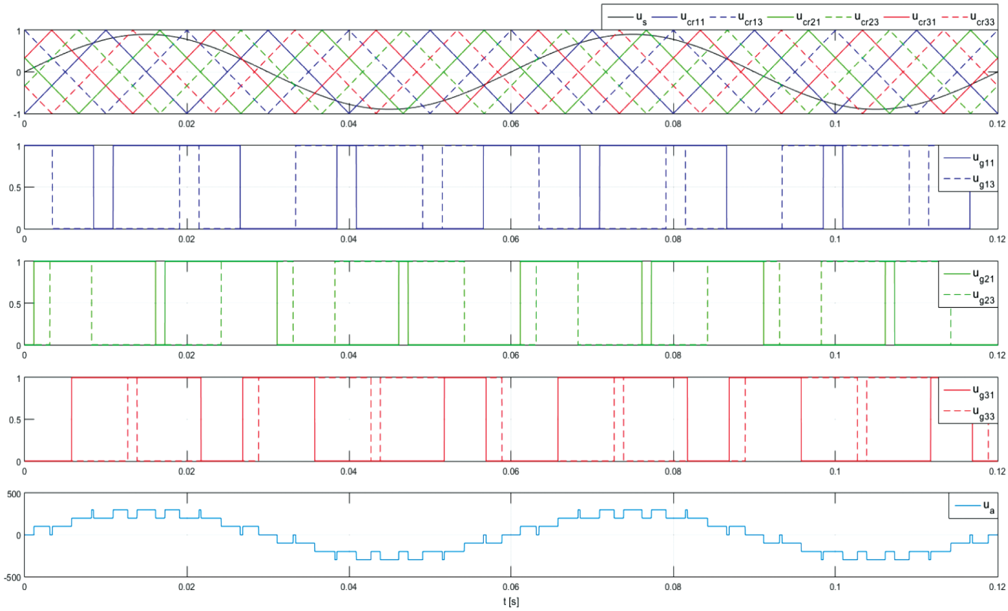


Fig. 3. Phase-shifted carrier signal modulation of a seven-level converter

In the top figure: black – modulating signal, lines marked in: blue, green and red – triangle waveforms for the upper valves of the left (solid lines) and right (intermittent lines) branches of each bridge. In the following three figures: control signals for the upper valves of the left (solid lines) and right (intermittent lines) branches of each bridge. The lower waveform: light blue – voltage generated at the converter input.

3. LLC resonant converter

The LLC converter finds numerous applications due to its benefits such as a wide range of loads, reduced switching losses thanks to zero-voltage switching and a low primary side valve shut-off current as well as secondary-side rectifier diode zero-current switching [4]. These soft-switching parameters could be obtained thanks to the transformer being in place and having integrated such features of the resonant circuit as leakage and magnetizing inductance. Also, the transformer ensures that the voltage levels at the DC balancing circuit are galvanically separated and adjusted accordingly by selecting the appropriate gear ratio.

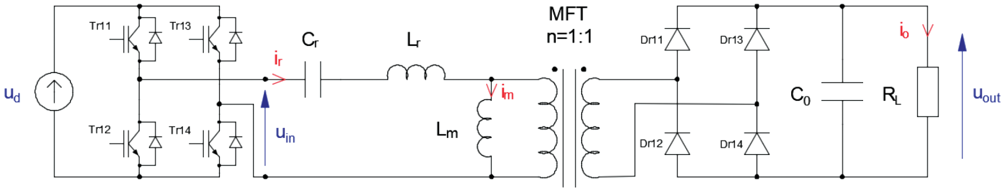


Fig. 4. LLC resonant converter topology

The Fig. 4 presents a typical topology of a full-bridge LLC resonant converter. The configuration features three basic parts:

a) semi-conductor valves made from IGBT transistors which are triggered to generate a rectangular voltage waveform. The bridge produces a bipolar rectangular voltage wave by alternately operating valve pairs: Tr11, Tr14 and Tr12, Tr13 at a fill rate of 50%. The dead cycle time between switches is necessary to prevent short-circuits and to enable the system to perform zero-voltage switching (ZVS);
b) the resonant circuit is characterized by resonance capacity C_r and two inductances – serial (leakage) L_r and magnetizing L_m. The gear is designated as *n*. The current flowing through the circuit supplies energy to the load by means of the transformer providing galvanic separation and adapting with the aid of the gear the output voltage to the required value;
c) on the converter secondary side, the diode bridge converts alternating to direct voltage, thereby powering the load. The output capacitor smooths out the rectified voltage.

Unlike pulse converters, a resonant converter adjusts voltage not by transmission of pulse energy, for example, from the voltage circuit to the current circuit, but by changing the resonant circuit's impedance in conjunction with changes in the operating frequency. This has the effect of changing the amplification factor of the transition function and thereby also the direct output voltage value. The existing designs of resonant converters using parallel or serial resonance were burdened with a number of limitations related mainly to the need for operating above or below resonant frequency, a very high rise of frequency in the case of zero-load operation, as well as high overvoltage and overcurrent occurring in the semi-conductor valves at resonant frequencies. The LLC converter is practically free from these shortcomings.

For an LLC converter, it is possible to determine a standardized direct voltage amplification characteristic (nU_{out} / U_{in}) for relative frequency (f_s / f_0) with a variable parameter of Q_e, also known as the resonant system's quality factor representing the converter's load condition.

The quality factor Q of a resonant circuit relates to vibrating systems and is in proportion to the ratio of energy W_m stored in a resonating system to energy W_t lost in a single vibration period, as in the following formula:

$$Q = \frac{2\pi \cdot W_m}{W_t} \tag{4}$$

In an electric resonant circuit, the quality factor gives an idea of its selectivity, or in other words, its ability to filter out waves with frequencies differing from the resonant frequency, as well as indicating the fade rate of free vibrations.

a) A resonant system's quality factor Q_e representing the converter's load:

$$Q_e = \frac{\sqrt{L_r / C_r}}{R_{L\_eqv}} \tag{5}$$

b) basic resonant frequency f_0:

$$f_0 = \frac{1}{2 \cdot \pi \cdot \sqrt{L_r \cdot C_r}} \tag{6}$$

c) second resonant frequency f_p:

$$f_p = \frac{1}{2 \cdot \pi \cdot \sqrt{(L_r + L_m) \cdot C_r}} = \frac{f_0}{\sqrt{1 + \frac{L_m}{L_r}}} \tag{7}$$

d) converter amplification is a relationship between output and input voltage. Fig. 5 depicts that amplification M_g can be expressed with electrical parameters of equivalent circuit of LLC converter:

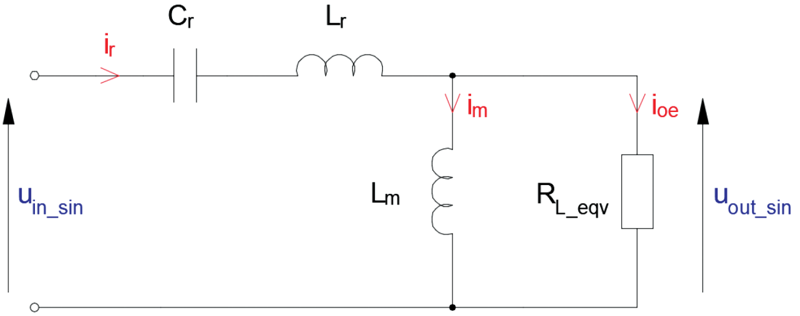


Fig. 5. Equivalent circuit of LLC converter

$$M_g = \frac{U_{out\_sin}}{U_{in\_sin}} = \left| \frac{jX_{Lm} \| R_{L\_eqv}}{(jX_{Lm} \| R_{L\_eqv} + j(X_{Lr} - X_{Cr})} \right| = \left| \frac{(j\omega L_m) \| R_{L+eqv}}{(j\omega L_m) \| R_{L+eqv} + j\omega L_r + \frac{1}{j\omega C_r}} \right| \tag{6}$$

Equations 8.1 and 8.2 are valid only for sinusoidal waveform.

After transformations and entering variables, f_n, l_n, Q_e:

$$f_p = \frac{1}{2 \cdot \pi \cdot \sqrt{(L_r + L_m) \cdot C_r}} = \frac{f_0}{\sqrt{1 + \frac{L_m}{L_r}}} \tag{7}$$

where:

L_r – resonant inductance,

C_r – resonant capacitance,

L_m – magnet inductance,

$R_{(L-eqv)}$ – load resistance converted into the primary side, relative frequency,

$\dfrac{f_n = f_{sw}}{f_0}$ – switching frequency,

$L_n = L_m / L_r$ – relative inductance.

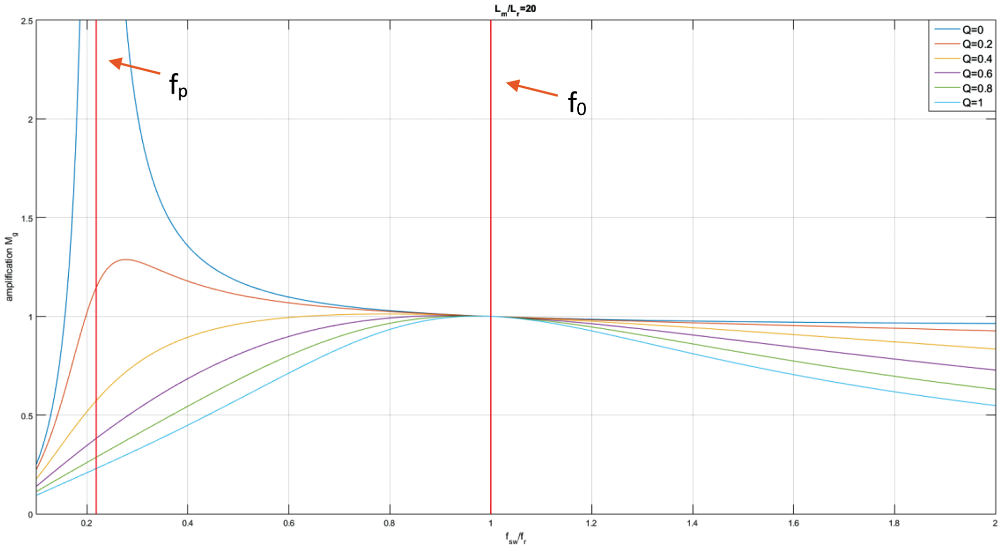


Fig. 6. Frequency amplification of the converter.Q = 0 to Q = 1 – quality factor of the resonant system, standing for converter load

The above characteristics shows a relationship between converter amplification and relative frequency for a range of loads, starting from idle represented by $Q = 0$, through increasingly greater loads represented by the rising value of Q, with magnetizing inductance 20 times greater than leakage inductance.

Bringing the inductance ratio down to 4, for example, means that for a wide range of loads (from $0.2 < Q_e < 1$), the operating (amplification) point is likely to change considerably in step with changes in frequency around resonant frequency. In this case, however, the converter supply voltage is balanced by a grid converter and so there is no need for amplification, leading to flattened amplification characteristics, as indicated in the figure below. Additionally, a high magnetizing inductance lowers the valve switch-off current.

Among the converter's most essential features is the fact that the generalized amplification value remains equal to 1 for a basic resonant frequency irrespective of the load applied. This means that a correctly designed unit will keep the LLC converter free from frequency fluctuations even where considerable variation of load is the case.

An LLC converter may operate in a (ZVS) area, in which transistors are switched on wherever the voltage at the transistor is zero, which eliminates power losses at switching. Also, a switch-off can be effected with a relatively low current, with the transistors capable of suppressing overvoltages unaided and helping to considerably reduce power losses occurring at transistor switch-off. Because of the resonating circuit current having sinusoid waveform, the current flowing through the diodes has a semi-sinusoid waveform, which means that for operation at resonant and sub-resonant frequencies, diode commutation takes place at zero-current. As a result, in this type of converter, power losses related to switching component commutation are kept to minimum across the effective operating range [4, 5].

4. Simulation

The simulation was carried out in a Matlab & Simulink environment. The main circuit and controls were built using a basic library and SimPower Systems library. The selected method (ode23s) of solving rigid differential equations was based on a modified Rosenbrok formula, in which the maximum step length was set at 10^{-6} s. Due to the complexity of the circuit, the multi-level input converter was simulated separately from the resonant converters. The system is not automatically adjustable; the parameters defining the power flow through the input converter were calculated beforehand for a specific operating point. This is part of the reason why a simplification was used by adding filters of the 2. harmonic at the output of each constituent bridge.

The simulation was carried out at both maximum and minimum supply voltage, the operation of the input converter was simulated at full load, while a single LLC converter was simulated at full power (corresponding to 1/8 of the total power) and at 10% of its rated power.

For both cases, the inverter operates correctly. The output voltage of each constituent bridge (violet) is 3300 V, the current flowing through the power line is in phase with voltage and its near-sinusoid wave points to a low THD. The green waveforms show voltage generated at the input terminals of the converter.

Output voltage (yellow) is 3 kV regardless of the voltage. Soft-switching conditions have been met, because the gating signal (green) is applied to the transistor when its voltage between collector and emitter (black) is equal to 0. The magnetizing current has a triangle waveform in both cases and turns off valves at approximately 40 A.

Fig. 9 presents a concept for the main circuit of the upgraded locomotive. The pulse controllers used in this application as traction converters and serial motors may be replaced with asynchronous inverters and motors. In a DC application, capacitor C_f forms together with choke L_f an input filter, while in an AC application, the same capacitor forms a common balancing circuit for each constituent diode bridge. The number of serially connected modules on the input side is 8 and depends on the blocking capability of IGBT transistors. The systems are switched by the aid of specially designed contactors. No provisions have been made for a return flow of energy to the alternating current grid.

Table 1. Simulation parameters

Output voltage	13,500–18,000 V 16 2/3 Hz
AC choke inductance and resistance	15 mH 0.1 Ω
Switching frequency for a single bridge of the input converter	1 kHz
Capacity of a capacitor of a single bridge	1.5 mF
Initial charge of a capacitor of a single bridge	3300 V
Resonant frequency of 2. harmonic filter	33 Hz
MFT primary side resistance	0.04 Ω
Leakage inductance on MFT primary side	87.5 μH
Resonance capacity	16.08 μF
MFT gear	1.1 : 1
MFT magnetizing inductance	7.639 mH
MFT secondary side resistance	0.033 Ω
MFT secondary side leakage inductance	72.3 μH
Resonant frequency	3 kHz
LLC converter switching frequency	2.7 kHz
LLC converter's output capacitor capacity	0.924 mF

Table 2. MFT transformer parameters

Rated power	300 kVA
Rated voltage	2971 V
Gear ratio	1.1 : 1
Power loss in the winding	800 W
Short-circuit voltage – absolute	0.1

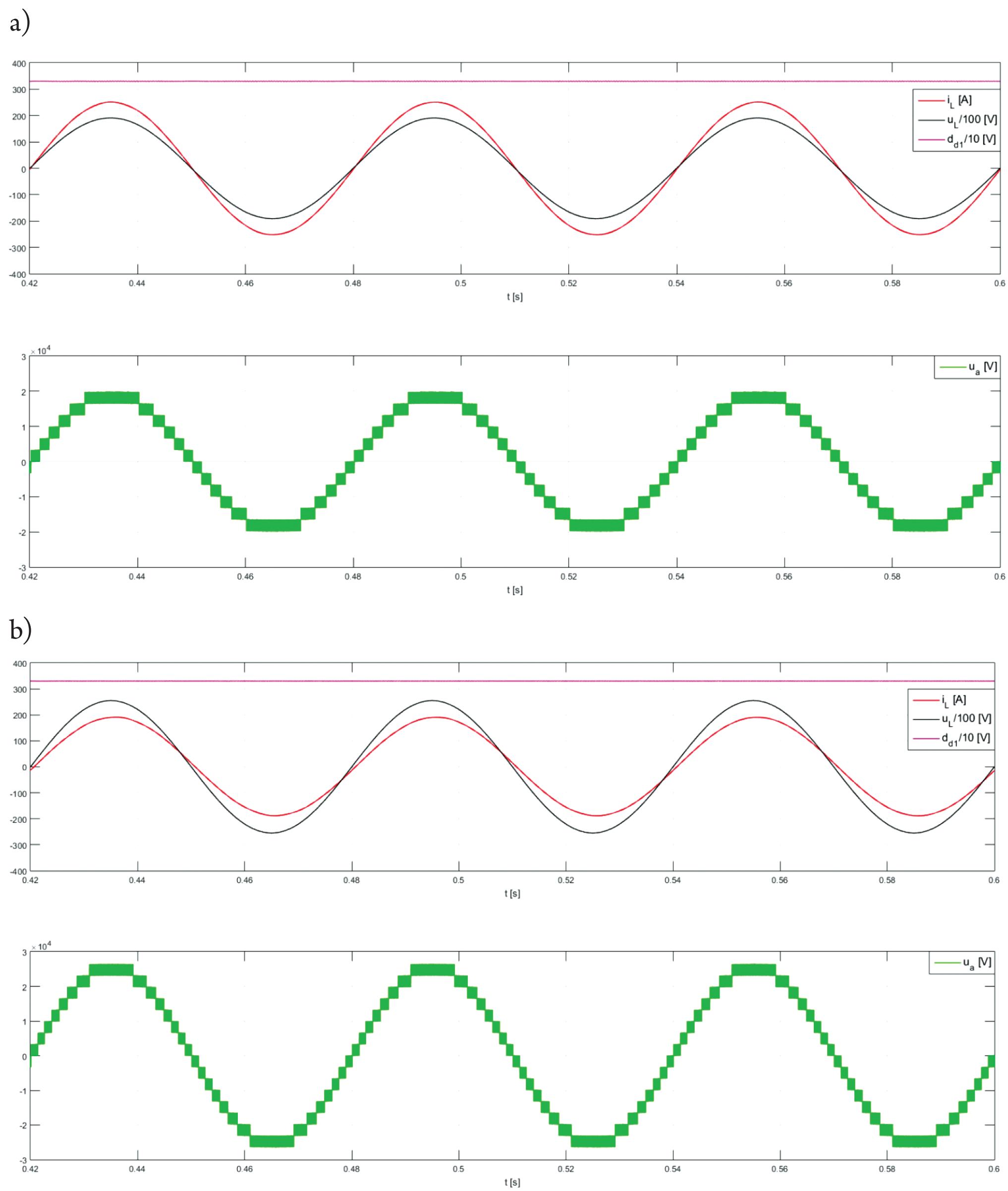
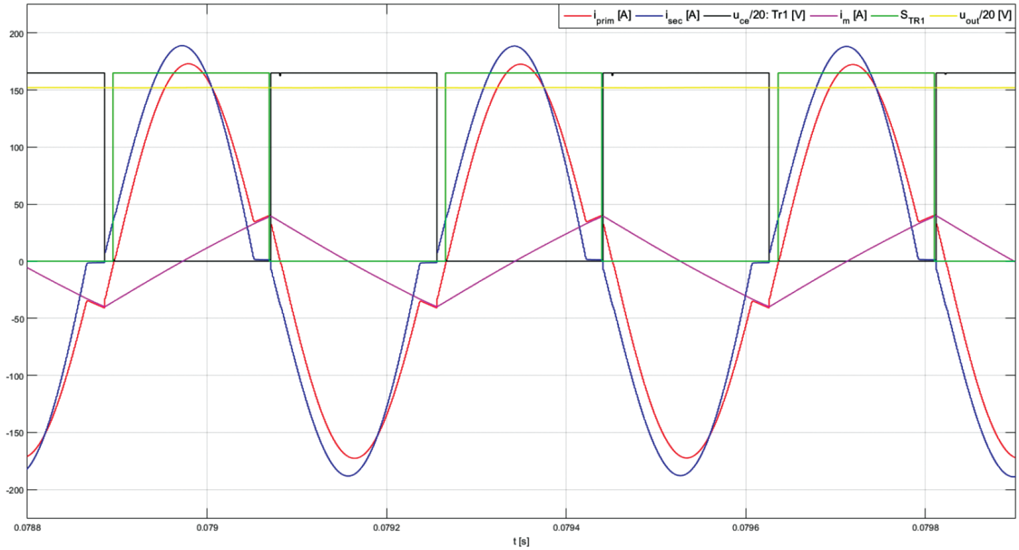


Fig. 7. Multi-level inverter waveforms for: a) supply voltage of 13.5 kV; b) supply voltage of 18 kV

a)



b)

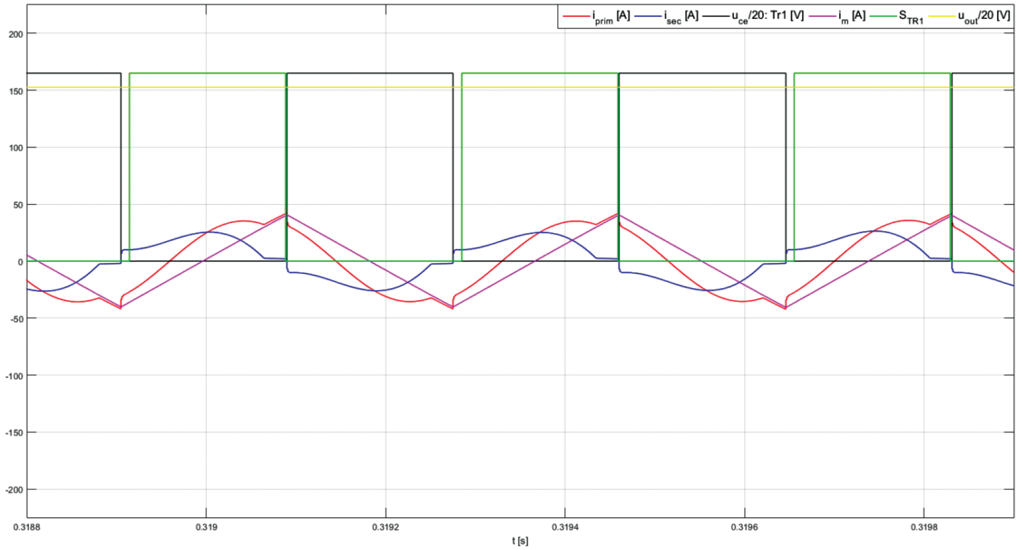


Fig. 8. Waveforms of a single LLC converter for: a) full load 300 kW; b) 10% of rated load – 30 kW

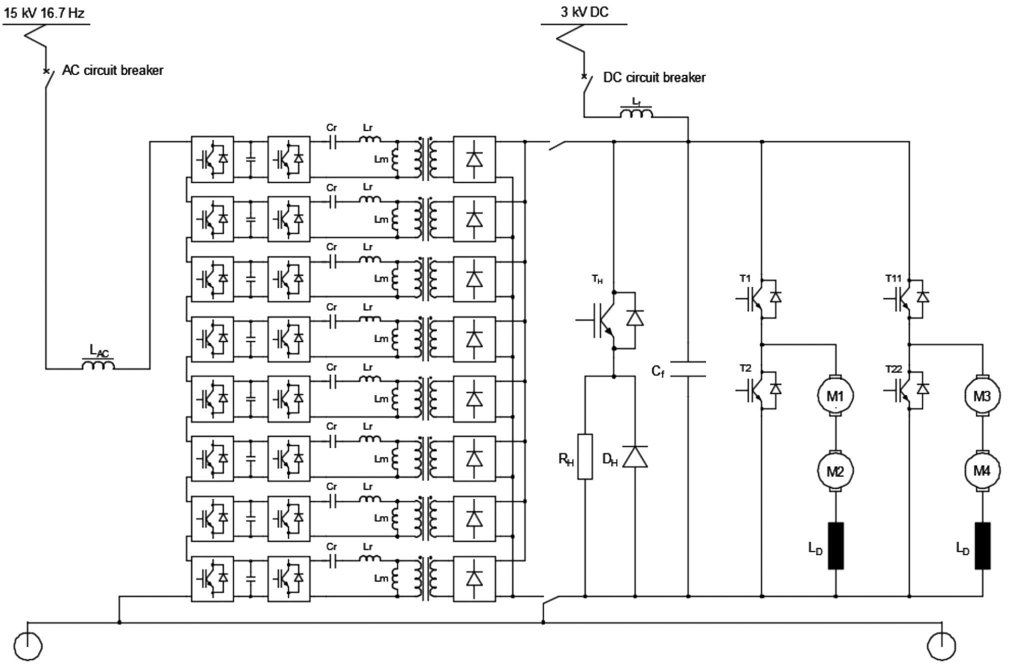


Fig. 9. The concept for the main circuit of the upgraded locomotive

5. Summary

This article presents the concept for upgrading the main circuit of EU 07 locomotive into a dual-system vehicle. The aim adopted herein was to develop a concept that would eliminate the need for using a traction transformer operating at grid frequency. A cascade converter system has been proposed, with medium-frequency transformers.

The simulations have shown that a multi-level input converter may be successfully built using IGBT transistors with a lower voltage rating, whereas the application of phase-shifted carrier signal modulation distributes the voltage evenly across each of the H-bridges, while also shifting the harmonics in the power grid towards higher orders as well as reducing electromagnetic interferences as a result of a decrease in the rate of voltage rise *dv/dt*. As a result, the input current is deformed to a small extent only. The system operates with a power coefficient approximating 1. The selected type of resonant converter enables reliable operation across a wide range of loads and good performance of valve commutation thanks to zero-load switching and low currents.

The benefits also include modularity and thereby extendibility to include additional modules in case of failure or the need for servicing or replacements. The disadvantages, on the other hand, include a large number of fully controllable components, complexity of the control system and a high price.

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