High Voltage Converter for Purpose to Minimizing of Weight of Traction Transformer

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***Abstract* – This paper describes the variants of realization of high voltage converter for purpose to minimizing of weight of traction transformer (so called "electronic-transformer"). The high voltage converter brings the possibility of using medium frequency transformer (with frequency for example 400Hz) instead of classical massive low frequency transformer (for trolley-line frequency 50Hz resp. 16.7Hz). This paper compares different variants of these high voltage converters – i.e. the topologies of indirect frequency converter, direct frequency converter (cycloconverters and matrix converters). Main attention is devoted to variants realized by authors (i.e. high voltage matrix converter).**

Keywords - High voltage converters; Single phase matrix converter; Electric vehicles; Medium frequency transformer

I. Introduction

Railroads in Europe use various systems of rated trolley-line voltage (see for example Figure 1). Using of AC traction systems brings the realization of vehicles with bulk traction transformer (see for example Figure 2). Some countries (Germany, Austria, Switzerland, Norway, Sweden) use old traditional traction system 15kV AC with reduced frequency – only 16.7Hz. Electric vehicles operated on these traction systems bring the problems of big weight of low-frequency traction transformers.

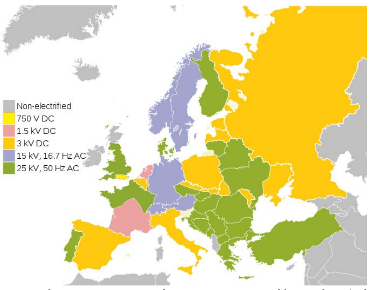

Figure 1. Traction systems in Europe railroads (picture from [1])

The Figure 2 shows the typical configuration of classical multisystem electric vehicles with the possibility of AC or DC input trolley-wire. High voltage (from AC-trolley wire) is reduced by transformer and rectified by active rectifier. Rectifier output (i.e. voltage-type of DC-link) supplies converters for traction drives and converters for auxiliary drives. DC-trolley wire is possible to directly connect to DC-link (through input LC-filter). Classical traction drive solution based on low frequency traction transformer is heavy and bulky.

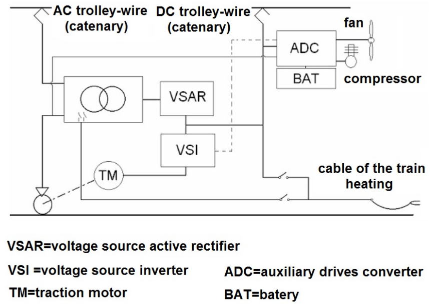

Figure 2. Configuration of classical multisystem electric vehicle

It is important to prepare new modification of the classical configuration for future purpose:

- for realization of new vehicles with high speed and high power (with reduced total mass of vehicle)
- for special types of vehicles - for example for bimodal vehicles "tram-train" with the possibility of operation in urban tram lines (low maximal weight of vehicles) and in main railroads lines (high speed, high power, AC-traction systems etc.)
- for cheap realization of universal multisystem vehicles (for future it is possible the minimizing of price of power semiconductor devices with the relatively constant price of classical transformer

II. Modern Solution with Medium Frequency Transformer

The configuration traction converter based on medium frequency transformer (MFT) is presented in Figure 3).

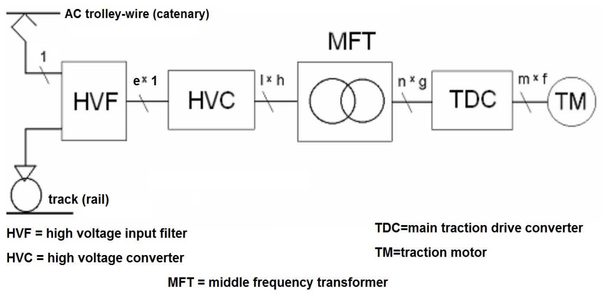

Figure 3. Principle of modern solution of multisystem electric vehicle with medium frequency converter

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Very complicated part is input high voltage filter (HVF) with high voltage converter (HVC). Figure 4 shows the basic variants of its realization. These basic variants are possible described by these topologies:

- Modular multilevel converter MMLC (see Figure 4A or chapter III.) – i.e. special version of direct frequency converter
- Input LC/C filter (see Figure 4B) – i.e. with indirect frequency converters with current source active rectifier or with matrix converters (see Figure 4B or 5 or chapter IV.)
- Input L-filter with multilevel rectifier (see for example 3-level active rectifier with clamped diodes in Figure 4C etc.)
- Joint input L-filter with serial connection of input side of indirect frequency converters with voltage source active rectifiers (see Figure 4D or chapter V.) resp. with direct frequency converter with cycloconverters (see chapter VI.)

Figure 4 shows only basic principles (input voltage is only double resp. triple with the maximal voltage on each semiconductor element). Practical realization with real semiconductor elements (for example high voltage IGBT with rated voltage 6.5kV) and real trolley-line voltage (rated voltage in Czech Republic 25kV/50Hz) needs high number of its levels (for example 13 or 14 levels).

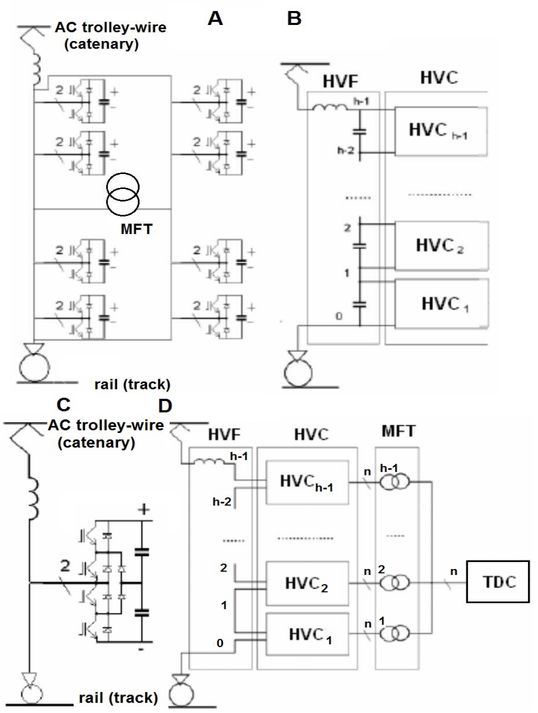

Figure 4. Input high voltage filter and high voltage converter

Variants according to Figure 4B and 4D bring the possibility of realization with only one joint medium frequency transformer MFT or with separated MFTs (one MFT for each level of HVC). Figure 5 shows the example of solution with 14 matrix converter with two MFTs (with traction induction motors with special double star stator's windings).

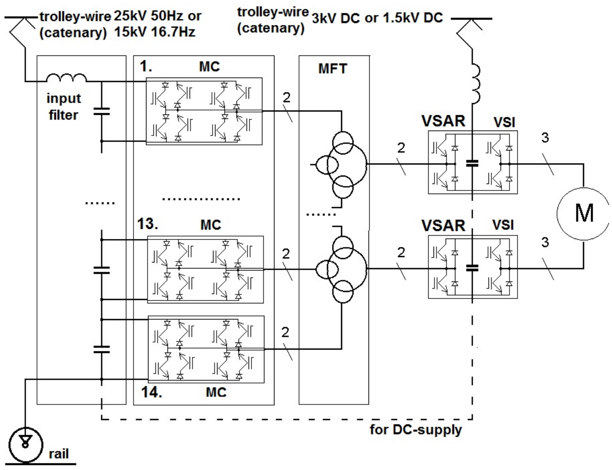

Figure 5. Input high voltage filter and high voltage converter

III. Modular Multilevel Converter

Figure 4A shows 2-level modular multilevel converter MMLC (i.e. 2 basic cells in each of arm, each output phase has top and bottom arms, i.e. this MMLC has 2x4x2x2=32 transistors).

High number of levels brings approximately sinusoidal input current with relatively low switching frequency (see detail in Figure 6).

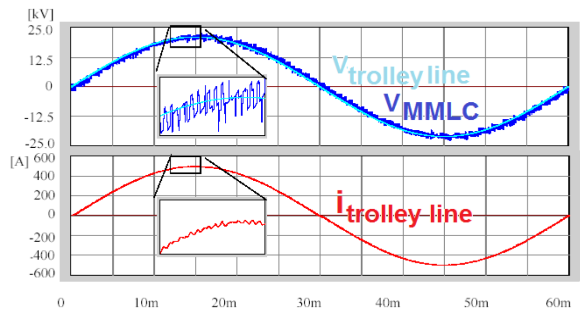

Figure 6. Input voltage and current for MLLC (picture from [3])

Output voltage and current from MMLC to MFT is possible to realize with the maximal pulse steepness (see Figure 7) limited by the maximal value of *dv/dt* with regard to parameters of the insulation of MFT etc.

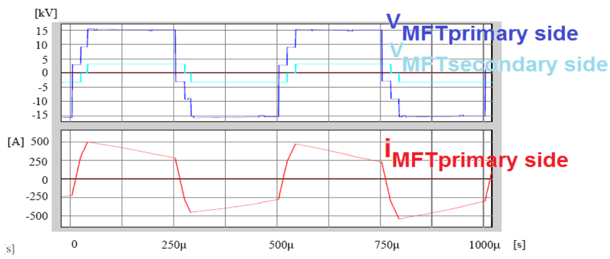

Figure 7. Output voltage and current from MLLC to MFT (picture from [3])

IV. Single Phase High Voltage Matrix Converter

Figure 8 shows the basic principle of configuration with two single phase matrix converters MCs with reduction of input voltage by high-voltage LC/C filter (with serial connection of capacitors). Sinusoidal low-frequency input is changed to voltage pulses (i.e. medium frequency signal) for joint MFT. This configuration brings advantages in the same value of voltage in each input capacitors (i.e. without complicated control algorithm for balancing).

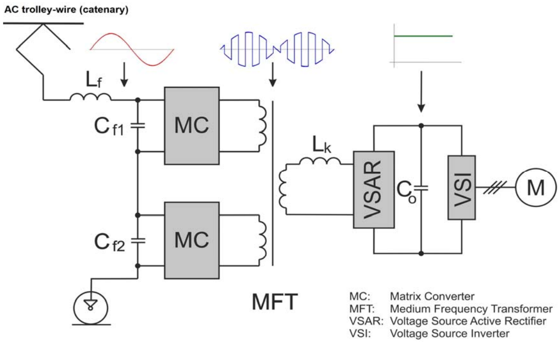

Figure 8. High voltage single matrix converters with joint MFT

Figure 9 shows the modular configuration with separated MFTs (each voltage level module has own MC, MFT and VSAR). Separated MFTs do not has magnetic coupling and this brings the necessity to use special control algorithm for purpose to obtain the same value of voltage in each input capacitors.

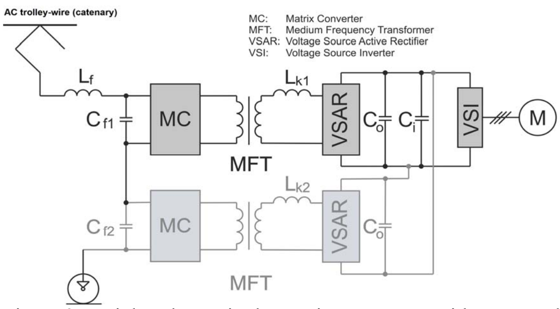

Figure 9. High voltage single matrix converters with separated MFTs (modular configuration)

Because actual value of input voltage it is not constant (see Figure 8), it is necessity to use special control algorithm for limiting of maximal magnetic saturation of MFT. Magnetic flux in MFT is:

$$d\Psi = \int_{t_1}^{t_2} u_{ind}\, dt \tag{1}$$

The eq. (1) brings the optimal situation with all voltage pulses with the same area:

$$\Delta\Psi_{1,q} = \Delta\Psi_{3,q} = \Delta\Psi_{5,q} = \frac{\Delta\Psi_{1,1}}{q} = -\frac{T_{Troll}\cdot U_A}{q\cdot\pi} \tag{2}$$

where: q is a number of output voltage pulses from MC by one period T_{Troll} of input trolley-line voltage

U_A and T_{Troll} are amplitude and period of input voltage

$\Delta\Psi_{j,q}$ is change of mg. flux during j-th pulse

It is possible to bring proof (by mathematical induction etc.), switching of elements of MC should be realized in these angles (switching time):

$$x_{j,q} = \arccos\left(1 - \frac{2\cdot j}{q}\right) \tag{3}$$

Figure 10 shows the illuminated examples (for small number of pulses i.e. for small switching frequency). Figures 11 and 12 show the practical examples of higher value of switching frequency.

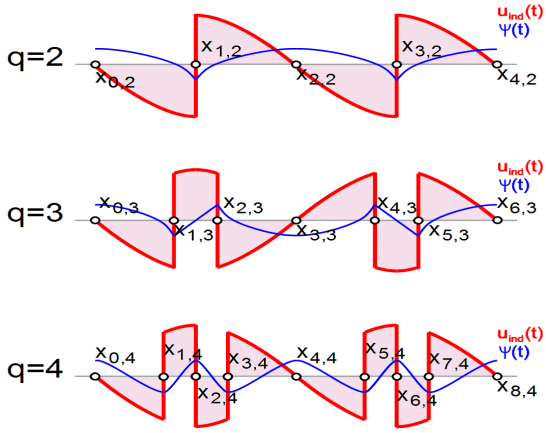

Figure 10. Mg. flux and voltage in MFT

Figures 11 and 12 show input voltage v_{input} and input current i_{input} (from trolley-line to input filter) and output voltage v_{output} from MC to MFT measured physical model of this traction drive in laboratory.

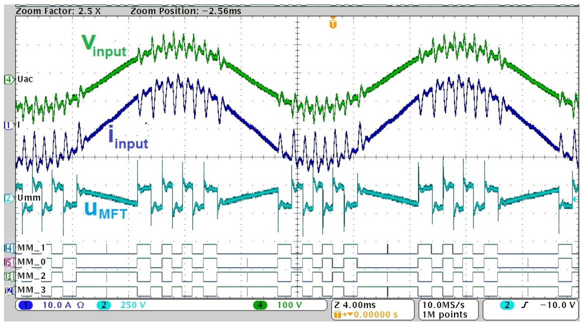

Figure 11. Average frequency in MFT 450Hz and input frequency 50Hz (i.e. number of pulses q=9)

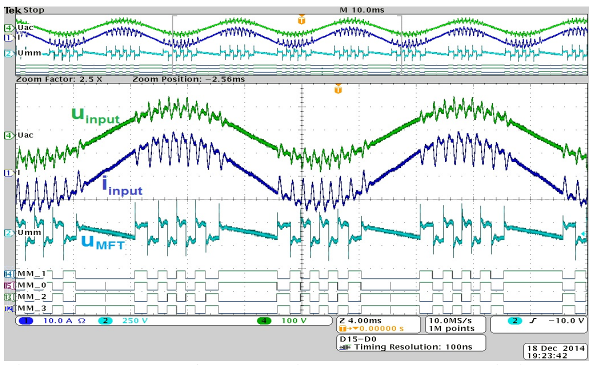

Figure 12. Average frequency in MFT 500Hz and input frequency 50Hz (i.e. number of pulses q=10)

Previous Figures 10-12 (and eq.(3)) show that actual switching frequency is not constant (during zero crossing of input voltage switching frequency is minimal and near magnitude switching frequency is maximal).

Figure 13 shows configuration of physical model and Figure 14 shows details of used converters. Control algorithms were implemented into DSP (Texas Instruments TMS320F28335).

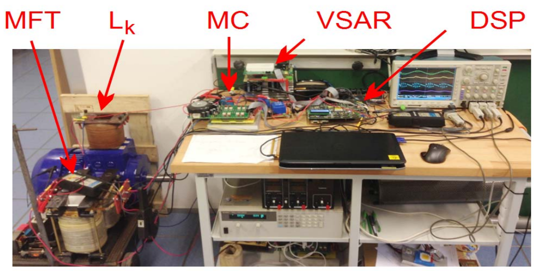

Figure 13. Physical model of electric drive with middle frequency converter (MFT), input inductance Lk, matrix converter (MC) and voltage sourced active rectifier (VSAR) controlled by DSP

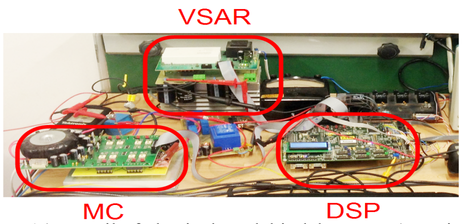

Figure 14. Detail of physical model in laboratory (see Fig.13)

V. Indirect Converter

Figure 15 shows the example of configuration with indirect frequency converters (with resonant soft switching and with half-bridges for purpose to minimize number of semiconductor elements and its switching power losses).

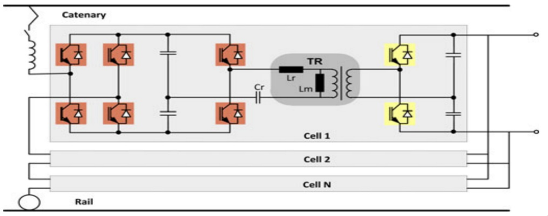

Figure 15. Modular structure with indirect frequency converter with half-bridge converter with soft-switching (picture from [9])

VI. Cycloconverter

Figure 16 shows the example of the configuration with input high voltage cycloconverter (only one voltage level). Its commutation is realized by special control algorithm with cooperation of indirect frequency converter in secondary side of MFT.

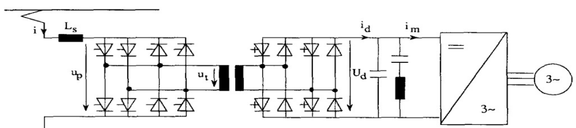

Figure 16. Principle of use the cyclocloconverter (picture from [9])

VII. Conclusion

This paper presents some variants of realization high voltage converters for traction purpose realized as experimental prototypes by some global manufacturers and by research departments. Main attention was devoted to variants realized by authors (i.e. high voltage matrix converter with joint MFT and modular connection with separated MFTs). For these variants was prepared control algorithms for matrix converters (algorithms for commutation and algorithms for constant mg. flux in MFT) and control algorithms for active rectifier in secondary side of MFT. These algorithms were implemented into DSP.

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