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Traction Drive with MFT - Novel Control Strategy Based on Zero Vectors Insertion

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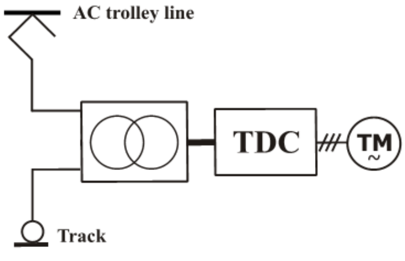
Abstract: This paper presents research motivated by industrial demand for special novel high voltage traction drive topology devoted to minimization of traction transformer weight against classical locomotives operates on both 25kV/50Hz and 15kV/16⅔Hz trolley voltages. The traction converter topology consists of: two single phase matrix converter + medium frequency transformer (MFT) + single phase voltage-source active rectifier. Measured results of steady state and selected transient states verifying of proper function of control algorithms. The new control strategy of traction converter based on zero vectors insertion has been proposed to smoothing taken trolley current.

Keywords: AC-AC conversion, Industrial electronics, Phase control, Matrix converter, Traction application, Converter Control.

1. 1. INTRODUCTION

This research has been motivated by the industrial demand for a design of traction converter with medium-frequency transformer (MFT) using matrix converters to replace the bulky main line transformer [SHE (2012)] used on board railway vehicles. Modern traction drives at the AC trolley use a topology with a transformer 25 kV / 50 Hz (Czech railways) or 15 kV / 16.7 Hz (Germany, Austria, etc.). The greatest attention is especially given to vehicles which can be operated on both networks. The Fig. 1 shows the schematic diagram of the drive topology of modern multi-system locomotives consists of special traction drives with double stator windings traction motor to spread DC bus line voltage to serial connection of two voltage source traction inverters.



TDC - Traction drive converter

TM - Traction motor

Fig. 1. Schematic diagram of a modern locomotives with main line traction transformer of 50 Hz or 16,7 Hz.

For multi-systems vehicles designed for both trolley networks (25 kV / 50 Hz and 15 kV / 16.7Hz) is necessary to use a large traction transformer connected at the vehicle input.

Increasing the frequency of the voltage on the primary side of the transformer can be achieved using medium-frequency transformer topology [Radvan (2011)]. Advantage of the medium-frequency transformer in comparison to classical transformer 50 Hz (16,7 Hz) is mainly in the size of the magnetic circuit, which can be significantly smaller. There are several ways how to increase frequency [Drabek(2011), Glinka(2003), Kalvelage(2003), Victor(2005), Steiner(2007), Villar(2009)], for example can be achieved by inserting frequency converters [Drabek(2011), Victor(2005)] directly to the primary (high voltage) side of the traction transformer in the vehicle. Principal diagram of the traction topology with medium-frequency transformer and indirect frequency converter is shown in Fig. 2.

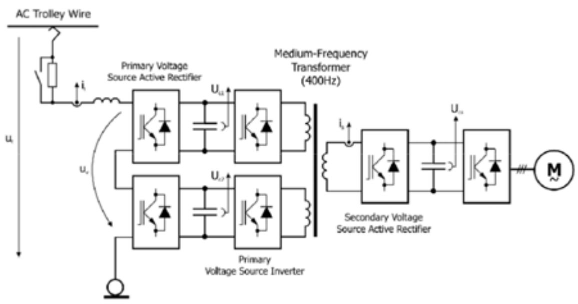


Fig. 2. Schematic diagram of the prototype vehicles with medium traction transformer and indirect frequency converter.

2. SINGLE PHASE MATRIX CONVERTER

The single phase matrix converter is the one possibility of input high voltage converter. Matrix converter can be understood as an alternative today standard indirect frequency converter [Wheelar(2002), Casadei(2007), Rodrigues(2007), Ortega(2012)].

Fig. 3 shows scheme of the traction drive with single phase matrix converter as an input traction converter which supplies middle-frequency transformer. The circuit consists of input high voltage filter (reactor L_F and capacitor C_F) connected to the input of the matrix converter which supplies middle-frequency transformer. The outputs of the transformer fed single phase active voltage rectifier and three phase voltage source inverter supplying AC motor. Filter with capacitor is situated in the input of the matrix converter and the inductive load (winding of the transformer) is connected at its output. These facts have to be taken into account to control the matrix converter –cannot short circuit input terminals and disconnect output terminals at the same time. Detailed single phase matrix converter topology is shown on Fig.4.

Fig. 5 schematically demonstrates basic ideas of operation principle (upper-hand part of the figure) of the traction topology with middle-frequency transformer. Input 50 Hz (16,7 Hz) sine-wave trolley voltage is cut to the middle-frequency voltage waveform (up to kHz) which is set on the input of the MFT. The secondary single phase voltage-source active rectifier processes the middle - frequency voltage waveform and control the DC bus line voltage as the source for the three phase voltage-source inverter.

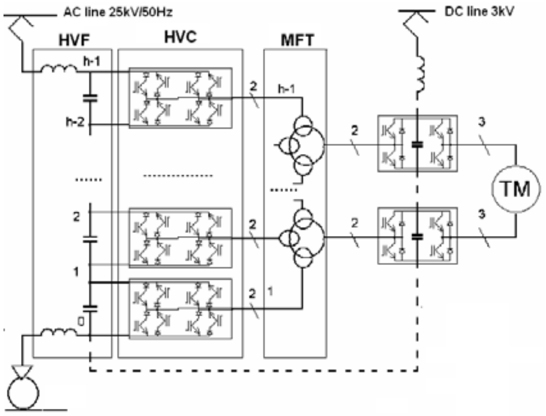


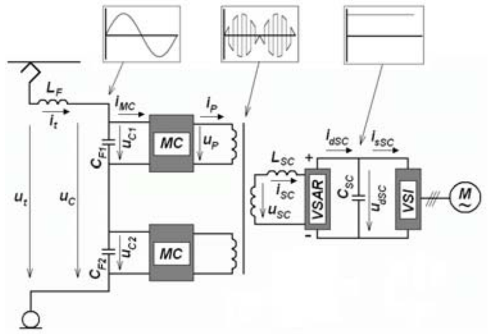
Fig. 3. Topology with single phase matrix converter as a primary high voltage traction converter.

Fig. 4. Detail of matrix converter and 4-step commutation of matrix converter

Detailed scheme of 1f matrix converter, switching states and details of converter commutations you can find in [Drabek(2011, 2009), Pittermann(2006, 2008a, 2008b)].

Described traction topology consists of primary and secondary converter and then we have to consider appropriate control switching of both converters for regulation algorithms of traction topology with MFT.

The basic idea of this control algorithm is following: secondary voltage-source active rectifier takes sine-wave phase current from middle-frequency transformer (two-value control) and square-wave control of the matrix converter which put together the phase current of output active rectifier to the 50 Hz sine wave taken from the trolley line. Amplitude and phase shift of the trolley line current is controlled only by output active rectifier.



MC - 1f matrix converter (primary converter)
VSAR - secondary voltage-source active rectifier
VSI - secondary voltage-source inverter
L_F - reactor of input filter **C_F - capacitor of input filter**
L_{SC} - clamping choke of the secondary voltage-source active rectifier

Fig. 5. Topology with single phase matrix converter as a primary traction converter.

3. EXPERIMENTAL RESULTS

Detailed block scheme of control algorithm of the matrix converter by secondary active rectifier with synoptical charts of mentioned control method is presented in Fig. 6. Principle of the control algorithm is described in [Drabek(2011)].

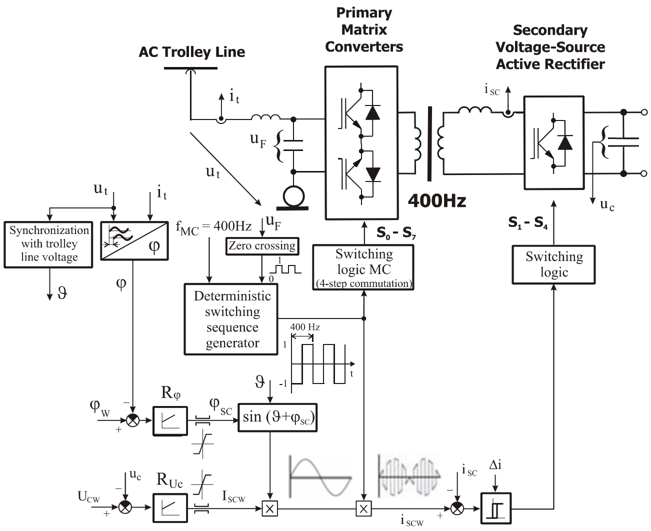


Fig. 6. Control algorithm scheme of the proposed traction drive

Amplitude of the phase current of output active rectifier is set by regulator of the output DC bus voltage Udsc. The matrix converter is simply controlled by square-wave control which put together the phase current of output active rectifier (400 Hz square wave modulated by 50 Hz sine wave) to the 50 Hz sine wave taken from the trolley line.

Fig. 7 and Fig. 8 show appropriate experimental measurements of properly working control strategy based on control algorithm of hysteresis control by output active rectifier. Experiment parameters in the steady state are follow: Ut=230 V, L_F=5 mH, C_F=20 uF, L_{SC}=1 mH, C_{SC}=4 mF.

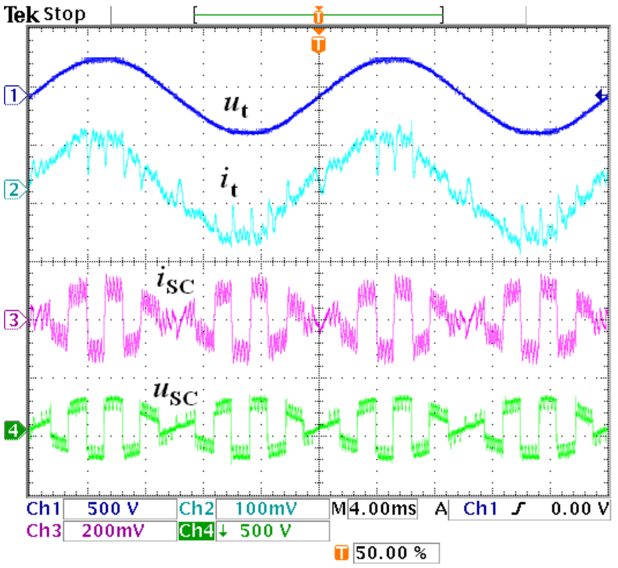


Fig. 7. Experimental results of traction drive with single matrix converter in rectifier mode

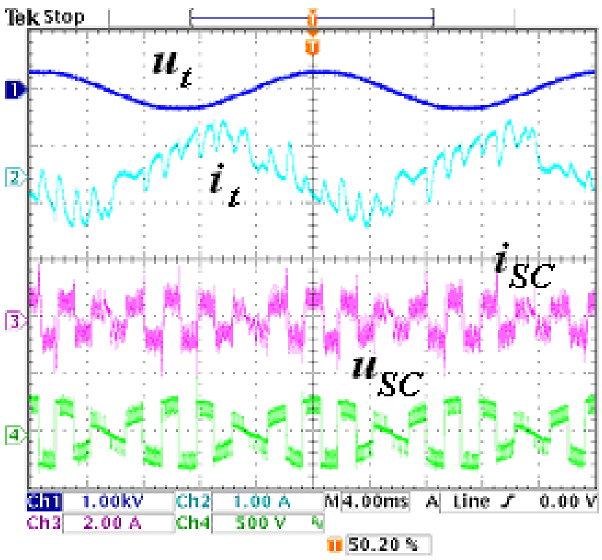


Fig. 8. Experimental results of traction drive with single matrix converter in inverter mode

The experimental model of traction drive has been directly connected to the power network grid to achieve rectifier and inverter mode as well. In Fig. 7 you can see variables of traction trolley line – voltage and current (ut and it) and voltage and current of the secondary active rectifier (u_{SC} and i_{SC}). In the figure the steady state of traction drive in rectifier mode with phase shift φ=0° is presented.

In Fig. 8 the experimental of steady state of traction drive in inverter mode (waveform of output current i_{SC} is in the opposite to waveform of output voltage u_{SC}) with phase shift φ=0° is presented.

Fig. 9 - 11 show experimental results of properly working control strategy in selected transient states.

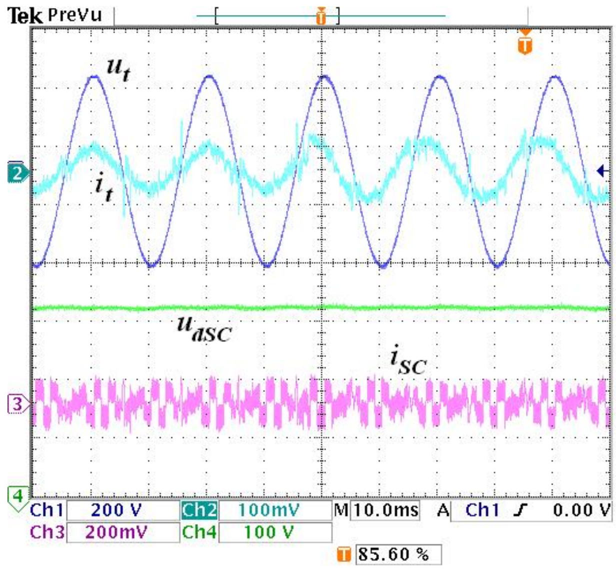


Fig. 9. Phase shift φ (between ut and it) change: 0 – 45°, rated power 2 kVA

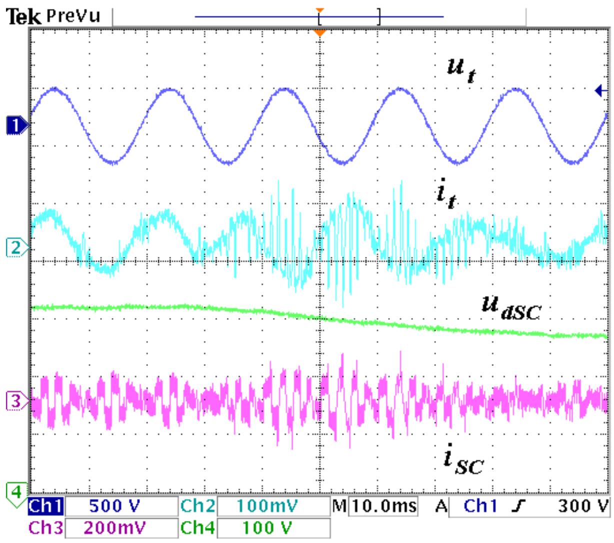


Fig. 10. Step change of UdSC, Ut=230 V, P=2 kW

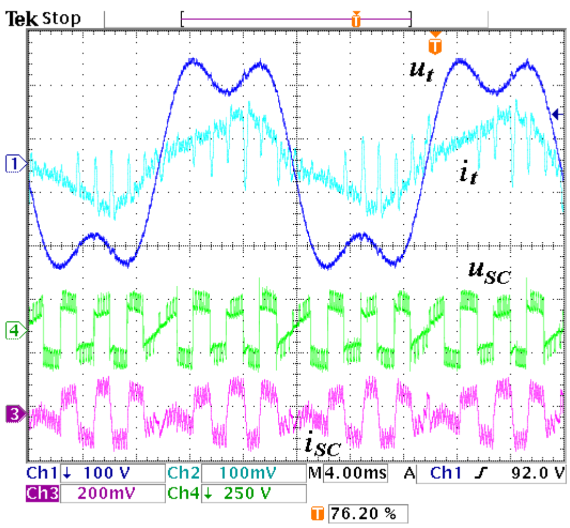


Fig. 11. The example of steady state under distorted power grid voltage

4. PROPOSED CONTROL STRATEGY OF MATRIX CONVERTER BASED ON ZERO VECTORS INSERTION

Control strategy of matrix converter using the zero vectors insertion enables setting the phase shift of input current against input trolley voltage (the phase). However this control strategy brings higher demands on input high voltage converter and designing of input converter. Therefore the phase shift control is secured by secondary low voltage active rectifier.

Default rectangular control of input matrix converters brings spikes of taken current from the trolley line (Fig.12 and Fig.13).

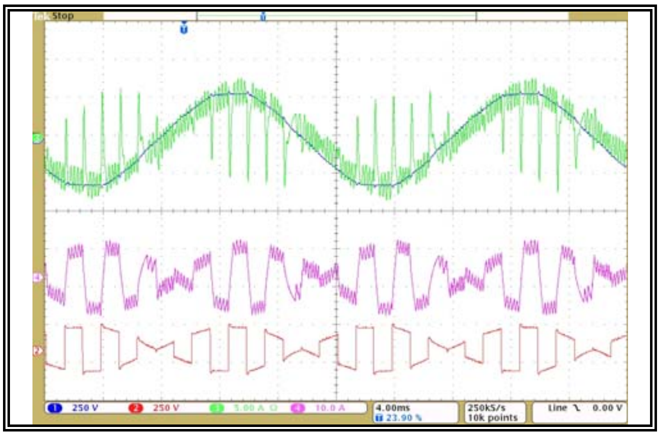


Fig. 12. Rectangular matrix converter control without zero vector insertion - rectifier mode

The principle of current spikes is shown in Fig. 14. During matrix converter switching the current has to change polarity due to the current commutation. In the matrix converter input current spikes appear as current commutation results. The spikes value depends on current amplitude and MFT leakage inductance which leads to the commutation time. It is difficult to eliminate both values therefore we have to think to modify the control strategy to suppress current spikes.

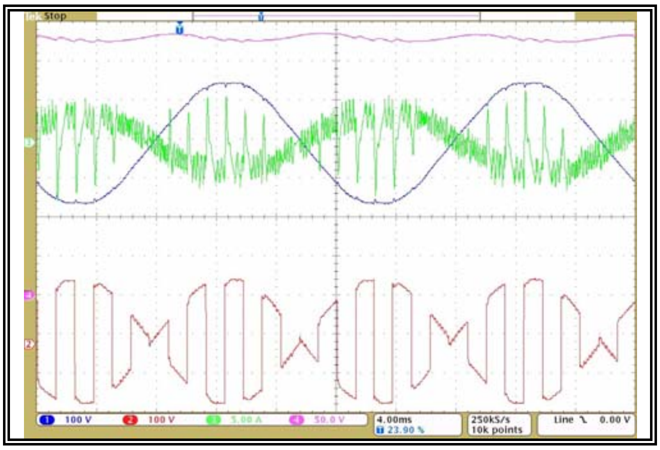


Fig. 13. Rectangular matrix converter control without zero vector insertion - inverter mode

One possible reason is zero vectors insertion to matrix converter strategy. Zero vectors are inserted at each transition matrix converter between "1" and "-1". Using this method is reduced charge that must accommodate input filter capacity when switching matrix converter..

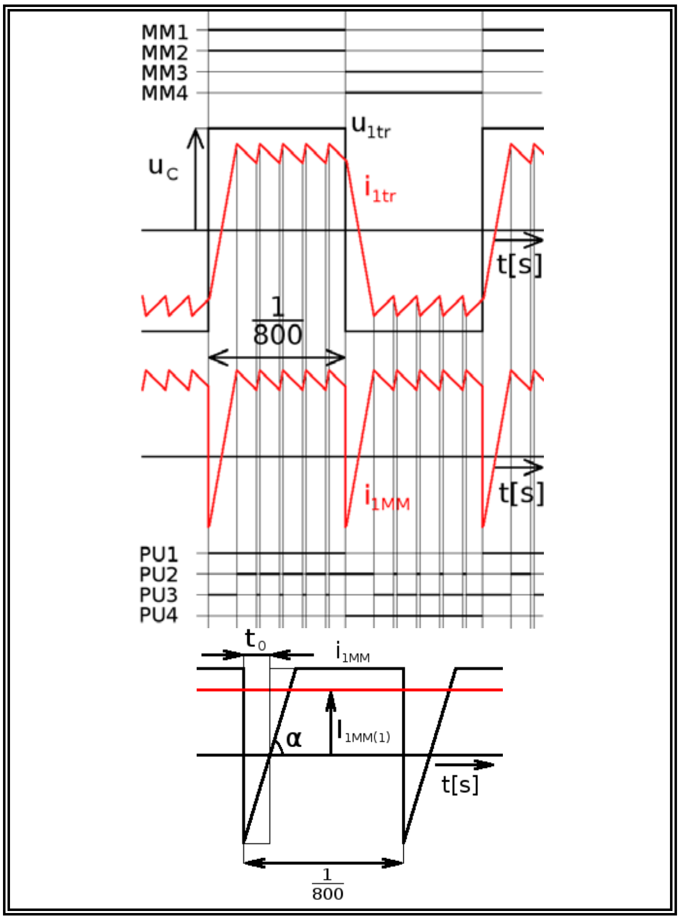


Fig. 14. Matrix converter current commutation (lower part - input matrix current, upper part - output matrix current)

The difference is shown in Fig. 15. During the zero vector, the matrix converter input is disconnected and the spikes are not presented in the taken current. The zero vector insertion time determines the suppression of negative current spikes.

However on the other hand zero vector insertion brings higher demand on the input filter designing. It is necessary to balance the request on current spikes suppression towards input filter capacitor value. Detailed information about input filter designing can be found in [Pittermann(2006)].

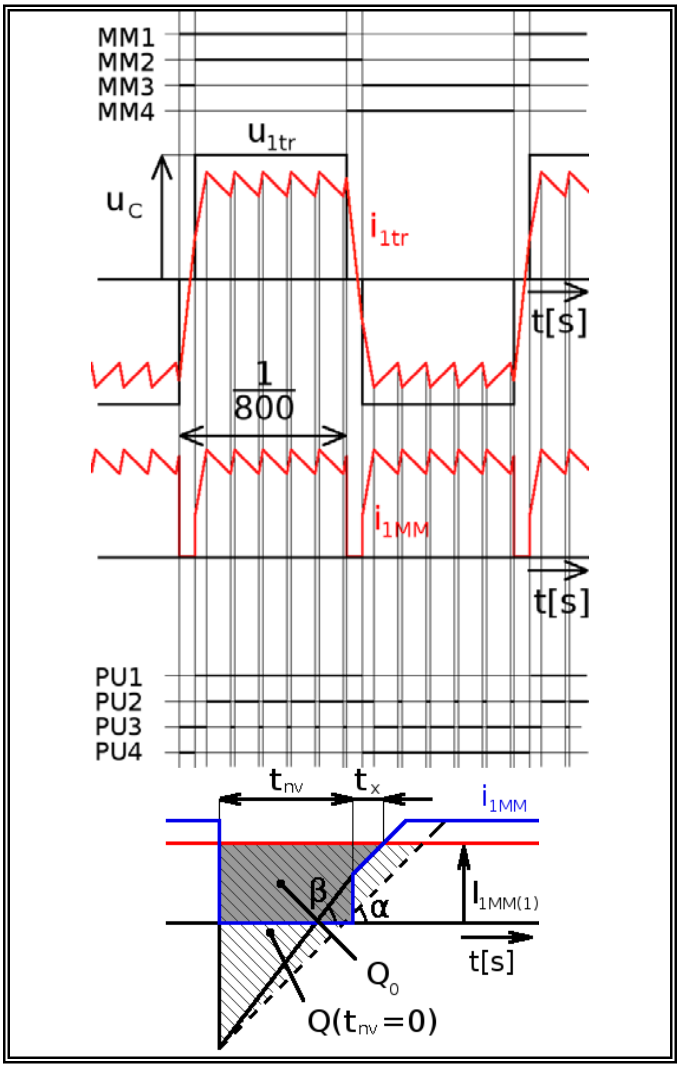


Fig. 15. Matrix converter current commutation with zero vector insertion (lower part - input matrix current, upper part - output matrix current)

Proposed control strategy of input matrix converter based on zero vector insertion brings suppression of current spikes of taken trolley current. Experimental verification of this control presents Fig. 16 and Fig. 17 under steady states in rectifier and inverter mode. Using zero vectors significantly reduce current spikes of taken trolley current which will appear also in low stress of switching devices, input filter etc. The EMC issue in the trolley line is other advantage of current spikes elimination.
This fact is demonstrated by measured frequency spectrums of taken current without and with zero vectors insertion (Fig. 17 and Fig. 18).

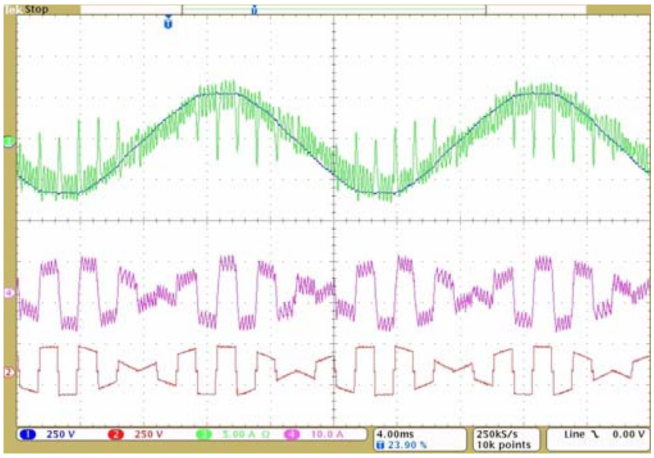


Fig. 16. Rectangular matrix converter control with zero vector insertion - rectifier mode

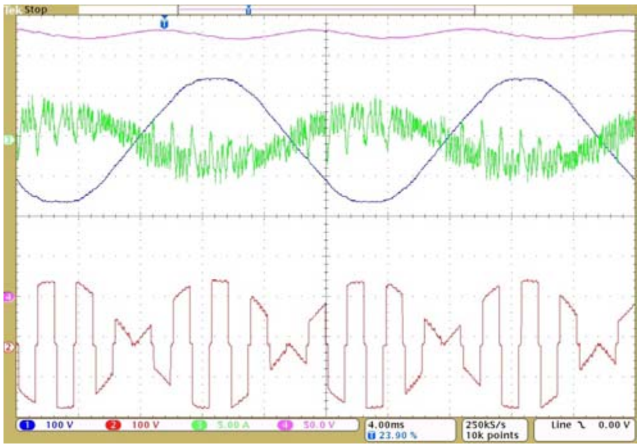


Fig. 17. Rectangular matrix converter control with zero vector insertion - inverter mode

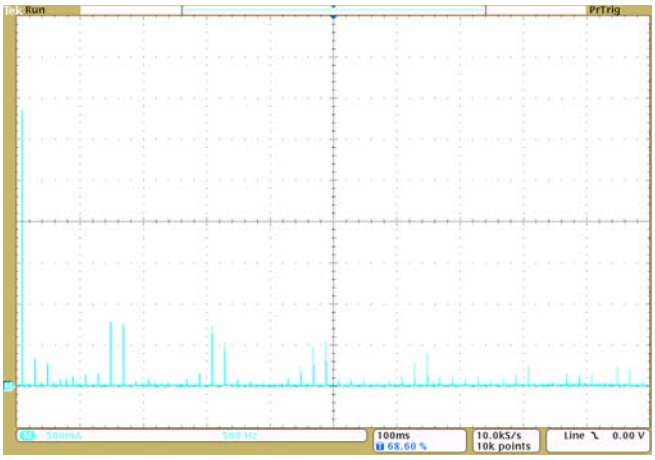


Fig. 18 Frequency spectrum of taken trolley current without zero vectors insertion

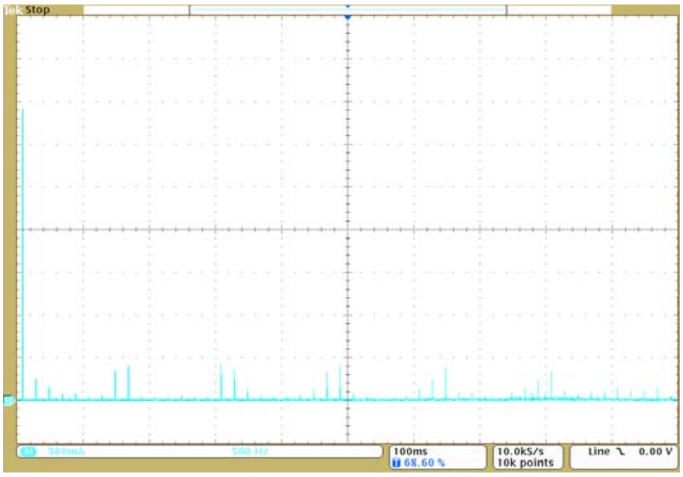


Fig. 19 Frequency spectrum of taken trolley current with zero vectors insertion

5. CONCLUSION

Upon the industry demand the innovative topology of the traction vehicles fulfill the extensive weight reduce requirements has been discussed.

The designed 4kVA laboratory prototype of novel traction drive with input high voltage 1f matrix converter employs model-based control system with phase shift control. Control method of traction drive using hysteresis control of secondary active rectifier and rectangular control of matrix converter has been proposed. These control methods ensure sinusoidal waveform and zero phase shift of taken current from trolley line.

A big advantage is an ability of keeping accurate value of demanded phase shift even under the distorted grid conditions and independently on all others quantities.

The presented experimental results confirm proper function of designed converter control with zero phase shift in rectifier and inverter mode as well. The actual research is focused on the improvement of traction drive behavior under distorted power grid voltage shown in these figures especially improvement of input current sine wave.

In this paper the method for the smoothing the matrix converter current with using zero vectors insertion during matrix converter commutation has been demonstrated.

The introduced traction converter topology has a good performance within the entire operating range. Considering the converter performance, reliability and size of the matrix converters, it can be concluded that the cascaded matrix converters are an interesting alternative to more conventional cascaded indirect frequency converters in the primary medium-voltage converter.

6. ACKNOWLEDGMENT

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