Metods for Voltage Ripple Mitigation on DC Side of Single-Phase AC\DC Converters

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Abstract – Traction converter with medium frequency transformer (MFT) presents current trend of modern locomotive drives topology. Traction drives based on MFT significantly reduce weight of bulky low frequency traction transformers and present modern traction converter topology. Single-phase converters connected to the AC trolley line suffer by second harmonic voltage ripple on DC side. Second harmonic on DC side presents serious issue in application with high power consumption such as railway application. This paper describes three passive and one active method for mitigation this phenomenon. For each one method the simulation model is created. At the end pros and cons of these methods based on created simulations are evaluated.

Keywords-Single-phase converters, Voltage ripple mitigation, Passive filter, Active filter

I. INTRODUCTION

On board traction transformers for AC-fed locomotives with trolley line frequency (50 or 16.6 Hz) are heavy and bulky. Medium frequency transformer improves that negative parameters, because higher frequency allow us to scale down size of the transformer. Single phase converters are used for convert input voltage to required frequency. Usually matrix converters or H-bridges with cascade sorted cells are used. Inverter with hard switching can achieve output frequency up to 2 kHz (3.3 kV IGBTs). This limitation is given by switching power loses of semiconductor devices. Soft switching is used for further increasing frequency which allowed us reach frequency up to 6 kHz (3.3 kV IGBTs). Traction drive topology based on MFT significantly reduces transformer weight and size due to the higher operating frequency (fig. 1).

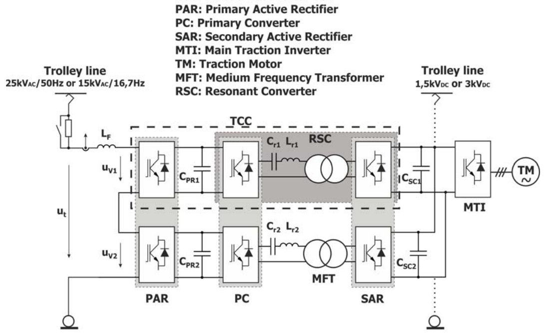

Figure 1. Railway drive with MFT topology

Single-phase converters connected to the AC trolley line generate second-order voltage ripple on DC side which is transmitted to other converters. Even traction motors are affected by increasing power loss and torque pulsation. This paper is concerned in comparison of chosen methods for keeping the voltage ripple at desired level. The problem can be solved by many ways. They are generally divided into passive and active methods. Passive methods consist of only passive components as storage for pulsation power generated by converter. Simplest passive method is design converter with large capacitor. That leads to high size, weight and cost. Next described solution is serial resonant passive LC filter added to DC link which is tuning on double trolley line frequency. Filter creating short circuit for ripple current and decreases requirement on main capacitor. Last passive method is a modified single-phase h-bridge PWM rectifier with power decoupling [1]. Active methods need passive components and additional switching components. Only one active method is mentioned in this paper is three-pole AC\DC converter [2]. The designing of smaller passive components is advantage of this method towards to regular passive resonant LC.

II. MITIGATION METHODS ANALYSIS

A. Mitigation by enlarging Capacitor

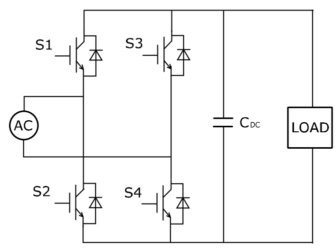

Figure 2. Single-phase AC/DC converter

This method uses only traditional full h-bridge with no other additional devices. Load consumed DC voltage and nearly constant current. Trolley line with power factor close to 1 does not create power when voltage and current is zero and create maximal power when voltage and current come on maximal level, which causing power pulsation. Capacitor must be

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large enough to fed load in time when input power is low and take in surplus energy when power is high.

The current control adopted from [2] was chosen to control this h-bridge. Block diagram is shown in fig. 3.

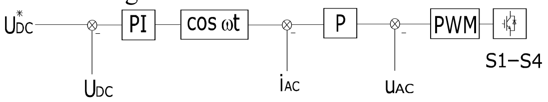

Figure 3. Current control block diagram

B. Serial LC filter

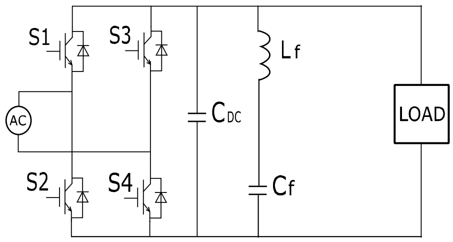

Figure 4. Single-phase AC\DC converter with LC filter

LC filter consist of serial resonance circuit, which is added in parallel with capacitor on DC side. Impedance of this circuit is not constant at all frequencies. It is tuned to create zero impedance for second-order ripple, in our case it is 100 Hz. Filter represents high impedance for other frequencies. Parameters are given by equation (1).

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

Control is remaining the same like previous method (fig. 3). Further analysis of LC filter is described in [3].

C. Three-Pole AC\DC Converter

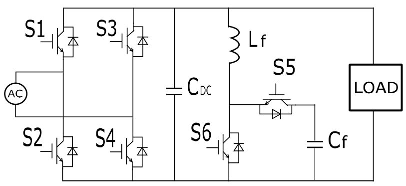

Figure 5. Three-pole AC\DC converter

On DC side of conventional converter is added separate phase z which consists of two switches and also capacitor and inductor as storage for ripple energy. The filtering phase absorb energy when voltage on capacitor C_{dc} increasing and inject energy to load when decreasing.

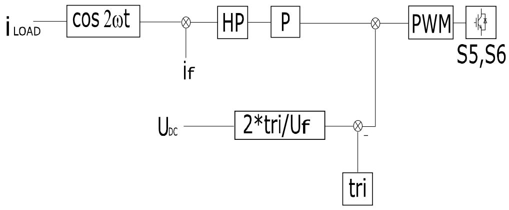

Figure 6. Filtering leg control block diagram

Control diagram for filtering leg is shown on fig. 6. Filtering leg has to absorb second order voltage ripple and operate at frequency two-time higher than grid frequency. Switching frequency is low as possible, because switches S5 and S6 causing additional switching loses and inject to DC voltage high order voltage ripple. Detailed description of control is in [2].

D. Modified Single-Phase H-Bridge PWM Rectifier With Power Decoupling

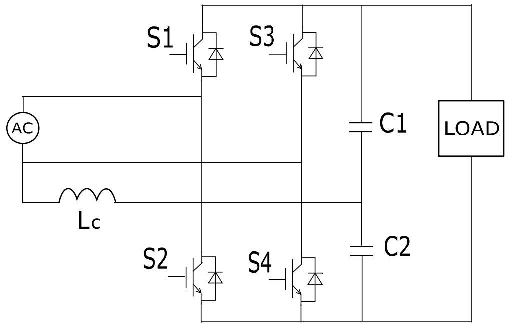

Figure 7. Modified single-phase h-bridge rectifier with power decoupling

Modification is in placement two capacitors in series instead one. Between neutral point and point between capacitors is connected smoothing inductor. Principle and control of this method is very complicated. Due to limited length of this paper I must refer on [1].

III. Simulation Results

This simulation was created to find out which method is most suitable for locomotive drive with MFT topology. AC trolley line has voltage 25 kV in Czech Republic. Drive will consists of 30 cells, which means that we get 833 V on one cell. H-bridges consist of 3.3kV IGBT transistors and on DC side is 1500 V. At present model of one cell of the drive is constructed. Voltage ratio of this model is 1:10 and power is ratio is 1:20. Parameter for simulation was selected with considering this model. Parameters of all components are shown in table I.

Table I.

Simulation parameters	
U_{dc}	150 V
U_{ac}	83.3 V (RMS)
L_a	1.5 mH
C_{dc}	4 mF
P_0	10 kW
f_s	2 kHz
Simulation parameters with larger capacitor	
C_{dc2}	24 mF
Simulation parameters for LC filter	
L_f	25 mH
C_f	100 µF
Simulation parameters for three-pole AC-DC convertor	
L_f	90 µH
C_f	6 mF
Simulation parameters for Modified Single-Phase H-bridge PWM Rectifier With Power Decoupling	
C_1, C_2	12 mF
L_c	50 µH

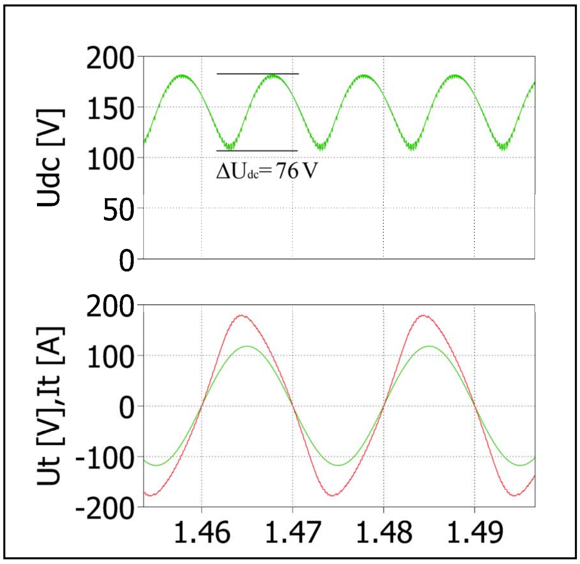

Figure 8. Waveforms of conventional H-bridge without mitigation

First simulation on picture 8 show behaviors of convertor with small capacitor and no other devices connect. We can see that output voltage is very fluctuating. Difference between maximal and minimal value is 76 V, which is 50.7% of average voltage. Grid voltage and current is not phase shifted which means that unity power factor is achieved, but current is deformed.

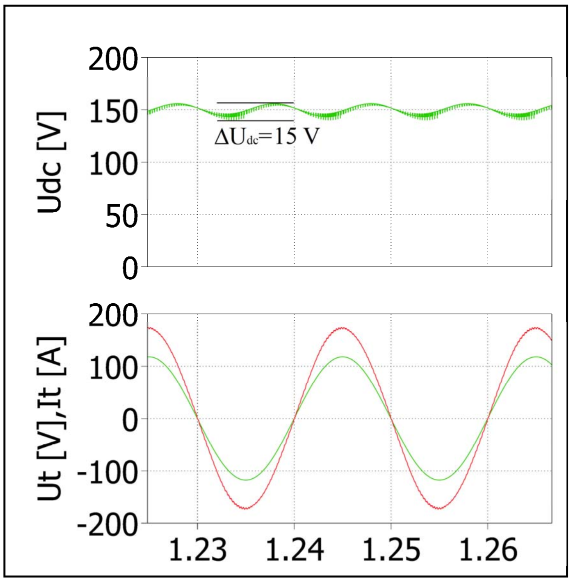

Figure 9. Waveforms of conventional H-bridge with larger capacitor

Simplest method for mitigate voltage ripple is simply increase capacitance of capacitor placed on DC-side. On fig. 9 is simulation with replaced capacitor which is six times larger than previous. Fluctuation voltage was mitigated to 15 V (10 % of average voltage). Unity factor is also achieved and input current is not deformed.

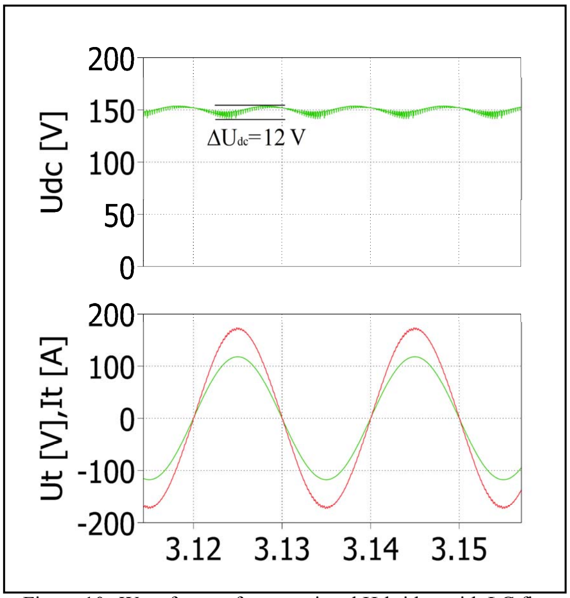

Figure 10. Waveforms of conventional H-bridge with LC fiter

In next simulation is added serial LC resonant circuit to the DC side. Voltage ripple is reduced to 12 V (8 % of average voltage). This method need very small capacitor (100 µF), but inductor is very large. Input current is sinusoidal and with unity power factor, exactly like with large capacitor.

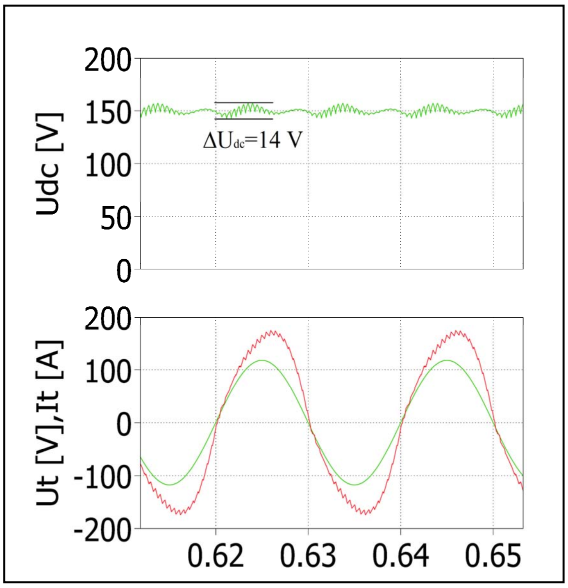

Figure 11. Waveforms of modified single-phase h-bridge

Simulation of modified single-phase h-bridge PWM rectifier with power decoupling mitigate voltage ripple to 14 V (9.3 % of average voltage). This method needs two relatively large capacitors and small inductor. On each capacitor is only half DC voltage. Grid current is deformed like as approximately same as with small capacitor without filtering.

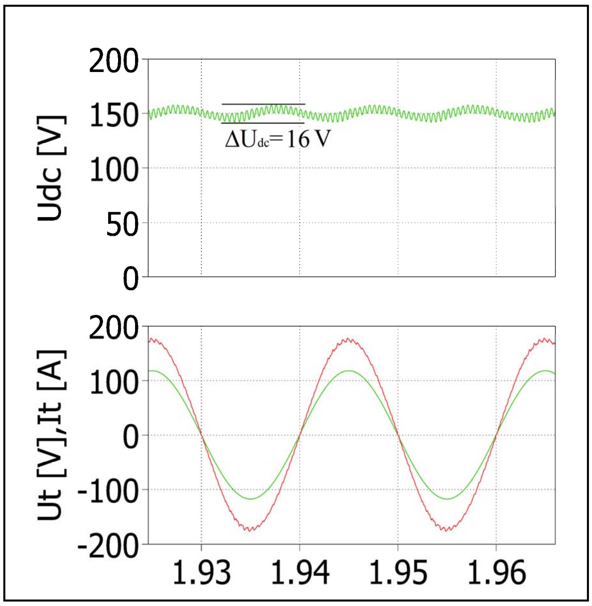

Figure 12. Waveforms of three-pole AC-DC converter

Last simulation is three-pole AC-DC converter. Voltage ripple was reduced to 16 V (10.7 % of average voltage). This method needs relatively small capacitor which operates on twice DC voltage. Grid current is curly on peaks which are caused by switching in the filter leg.

IV. Conclusion

Second harmonic voltage ripple represents main drawback in modern locomotive drives and can cause voltage pulsation on DC side. Pulsation has bad influence on traction motor and lifetime of transmission. There are many methods for reduce this pulsation. Every method has pros and cons. Four simulations were created to find out which method is most suitable for designer needs.

Enlarged capacitor is simple methods with good dynamic response. We need large capacitor to achieve acceptable voltage pulsation level. That significantly increasing size and weight, which is main reason for develop other methods.

LC filter allow use of smaller capacitor. Disadvantage is large inductor, which is big and heavy. Also, dynamic response is bad and LC filter cause additional power loses.

Three-pole AC/DC converter has much smaller passive components and much better dynamic response than passive LC filter. This converter contains two additional switches, which increase cost and switching losses. Another drawback is that, voltage on filtering capacitor is two time higher than voltage on DC capacitor.

Modified single-phase h-bridge has two relatively large capacitors with half of DC-voltage on each of them. No additional switches are needed and dynamic response is comparable to three-pole AC/DC converter. Main drawback of this method is deformation of grid current, which have bad influence on grid.

In future work presented methods will be implemented to DSP and tested on laboratory model to confirm simulation results.

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