MATEC Web of Conferences **180**, 05002 (2018) https://doi.org/10.1051/matecconf/201818005002
MET'2017

Effect of the supply voltage fluctuations on the efficiency of the technique of shaping the current spectrum generated by VSI traction drive

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Abstract. The issue of interfering influence of traction vehicles on railway traffic control systems is a serious problem posing a threat to railway traffic safety. This issue is gaining in importance as more and more vehicles equipped with traction inverters are put into service. Current harmonics generated by traction vehicles equipped with voltage source inverters can be controlled in such a way that they do not exceed the limits imposed by railway operators. One of the current harmonic control techniques, proposed by the authors, is the use of a combination of SHE (Selective Harmonic Elimination) and SHM (Selective Harmonic Mitigation) techniques to control the traction voltage source inverter. In this article, the author present the results of investigations on the influence of supply voltage fluctuations on the efficiency of shaping techniques of the current harmonic spectra taken from the DC network by VSI traction drive system, using the SHE and SHM modulation techniques. Regarding the fact that in 3 kV DC electric traction systems, fluctuations of the vehicle's supplying voltage are accepted in a wide range, it is necessary to determine the influence of voltage changes on the proposed modulation techniques. The research object is a simulation model of traction drive which consisting of an asynchronous motor fed by a voltage source inverter. The simulation model was verified by the means of measurements performed at a low scale laboratory stand. Analysis of the tested techniques when supplying voltage is fluctuating, allows to evaluate their usefulness in real operating conditions. The results obtained for SHE and SHM techniques were compared with SPWM modulation.

1 Introduction

The modern traction vehicles are commonly equipped with power electronics devices to provide fluent and dynamic control over torque of traction motors. This type of devices are known to be the significant source of current harmonics which may occur as the distortion for railway signalling system. That is the reason why railway operators provides limits for admissive amplitudes of current harmonics generated by traction vehicles. For example for Polish Railways (PKP) this limits are formulated in [2]. Fig.1 ('Limits Icat') presents mentioned above limits only for frequency band 1300-3100 Hz. This frequency band is known to be critical because of high level of current harmonics generated by traction drives and relatively low attenuation of vehicle's input filter. This was the motivation for the author to take this frequency band under consideration.

For purposes of this work 'Limits-Icat' were recalculated on the DC-link side of a low pass gamma-type input filter as the 'Limits-If' (Fig. 1). The current I_{cat} can be easily recalculated to current I_f (Fig.2), using formula (1) where impedances of the choke $Z_{Lf}(j\omega)$ and the capacitor $Z_{Cf}(j\omega)$ are taken under consideration. This formula is correct only for high frequencies where impedance of input filter can be assumed linear:

$$I_f(j\omega) = I_{cat}(j\omega)\cdot\left[\frac{Z_{Lf}(j\omega)}{Z_{Cf}(j\omega)}+1\right] \qquad (1)$$

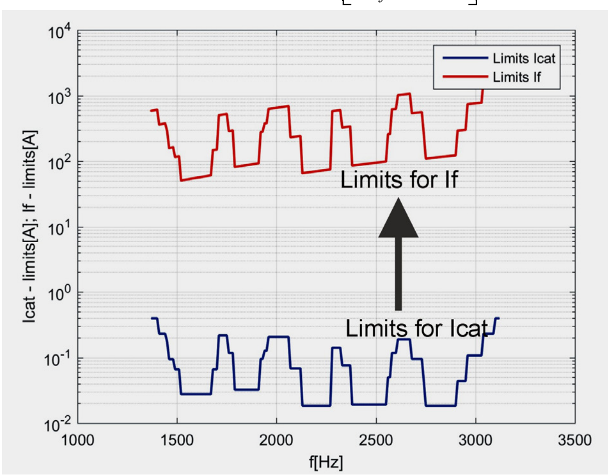

Fig. 1. Limits for catenary (I_{cat}) and recalculated for DC-link (I_f) current harmonics, generated by a traction vehicle in the frequency band between 1300 and 3100 Hz;

One of the opportunities to reduce the level of distortions generated by vehicles is to apply multilevel

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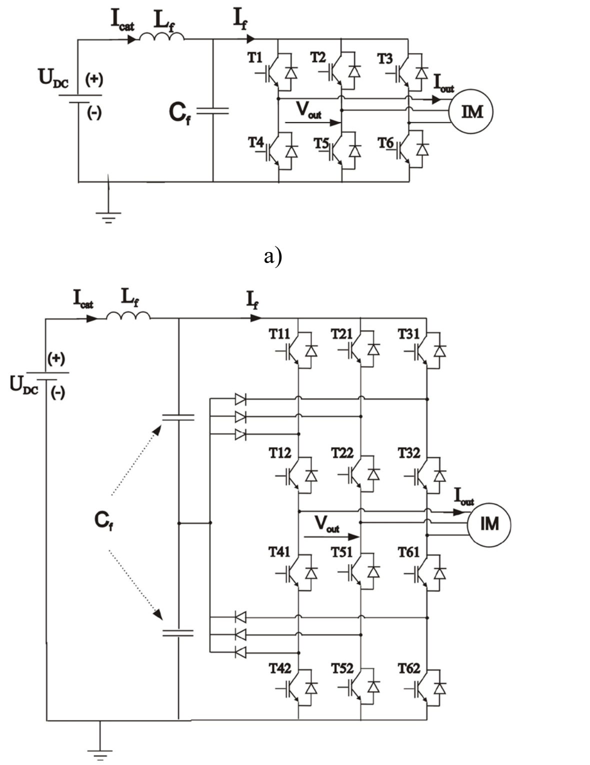
traction converters instead of two-level ones [1] [4]. However, replacement of two-level traction inverters with three-level do not solve finally the problem of distortions generated by traction vehicles. The suitable control algorithm is required.

2 Problem description

In previous works [7, 8, 11] the Author presented the possibility of application of selective harmonic elimination (SHE) and selective harmonic mitigation (SHM) techniques to eliminate or control chosen current harmonics generated by traction drive to fulfil limits from Fig. 1. In mentioned analysis the DC traction power supply system was assumed to be modelled as perfect voltage source because voltage fluctuations were not in the scope of the conducted research. In this paper the Author took under consideration the influence of supply voltage fluctuation on efficiency of SHE and SHM techniques in traction current harmonics control.

The issue presented in this paper is to prove that change of supplying voltage can be compensated with change of modulation index of voltage waveform generated by traction inverter with sustained control of chosen current harmonics bellow assumed limits. The permissible changes of voltage in 3 kV DC traction system are set between 2000 and 3600V [9]. The task is to change the supplying voltage U_{DC} in the range set by the standard and change modulation index in such a manner to keep traction drive in one operating point described by the constant value of inverter's voltage basic component (U_{out}). Afterwards the corrections to harmonic control strategies must be implemented to keep current harmonics below assumed limits.



a)

b)

Fig. 2. Schema of the traction VSI, a) two level b) three-level.

3 Simulation model

The traction multi-drive simulation models were implemented using the Matlab Simulink environment. The two-level and three-level NPC VSI topology were chosen (Fig. 2). Simulation models of 500 kW induction traction motors were implemented. The measurement verification of simulation models used in this work was conducted on low scale laboratory model based on DSpace 1104 platform and presented in [7, 8, 11]. Simulation results were carried out for quasi-steady states of the analysed drive system with usage of time domain transient simulation option. The supply voltage was modelled as the perfect DC voltage source with variable voltage magnitude U_{DC}.

4 Selective harmonic elimination - SHE

The SHE modulation is one of the non-carrier based techniques. It was described for the first time in 1960s [10] and it was developed by Patel and Hoft in [5] [6]. When voltage harmonics are not eliminated but their values are set on certain values the technique is called Selective Harmonic Mitigation (SHM) [3]. SHM technique is still taken into account in the latest research and industrial applications [12, 13]. Both techniques (SHE and SHM) are based on direct determination of switching angles (time points) for VSI's transistors by solving the set of nonlinear equations, developed from the Euler's coefficients of Fourier series (2):

$$f(\omega t) = a_0 + \sum_{n=1}^{\infty} [a_n \sin(n\omega t) + b_n \cos(n\omega t)] \qquad (2)$$

where: a_0, a_n and b_n – coefficients described by the Euler's formulas.

In this paper the quarter-wave symmetry of voltage waveform is assumed. In this case for two-level inverter coefficients a_0 and b_n are equal zero and a_n, can be described as follows:

$$a_n = \begin{cases} \dfrac{4 \cdot U_{DC}}{2n\pi}\left[1 + \sum_{i=1}^{N}(-1)^i \cdot 2\cos(n \cdot k_i)\right] & \text{for odd } n \\ 0 & \text{for even } n \end{cases} \qquad (3)$$

Therefore for three-level inverter a_n, can be described as follows:

$$a_n = \begin{cases} \dfrac{2 \cdot U_{DC}}{2n\pi}\left[1 + \sum_{i=1}^{N}(-1)^i \cdot \cos(n \cdot k_i)\right] & \text{for odd } n \\ 0 & \text{for even } n \end{cases} \qquad (4)$$

where: N- number of switching angles, k - switching angle.

Using N switching angles in quarter period N-1 voltage harmonics can be eliminated (or controlled) from the spectra of inverter's output voltage ($V_{out}(f)$). Regarding [7, 8, 11] using this technique, DC side current harmonics spectra can be controlled indirectly to match it to the assumed limits. In next part of this paper the case of U_{DC} variation for one inverter's operating point will be taken under consideration.

5 Assumptions

In this work one operating point of the two and three-level traction inverter was taken under consideration with different values of supply DC voltage (U_{DC}). The parameters of analysis starting point are presented in Table 1.

Table 1. Operating point parameters.

Inverters fundamental frequency (f_{fal})	**60 Hz**
Modulation index (M)	0.7
Voltage fundamental component (U_{out})	1200 V
Motor phase current (I_{ph})	215 A
Supplying voltage (U_{DC})	3400 V
Number of switching angles (N)	5

The simulations were provided for one inverter with one motor but the limits for I_{cat} current [2] were divided by 4 ('lim/4') for case of vehicle driven by 4 motors and by 8 ('lim/8') for case of double traction units. The limits were recalculated od DC-link current I_f regarding equation (1). The inductance and capacity of gamma filter were assumed as follows: L_f = 8.7 mH, C_f=6.5mF The aim of the study is to select a control strategy to meet the most restrictive 'lim/8' limits. for operating point from Table 1 the elimination of the lowest voltage harmonics was chosen (5^{th}, 7^{th}, 11^{th} and 13^{th}) On Fig. 3 it is shown that this control strategy is effective for 3400V U_{DC}. All current harmonics ale below assumed 'lim/8' limits. In next part of this paper a variation of U_{DC} will be implemented.

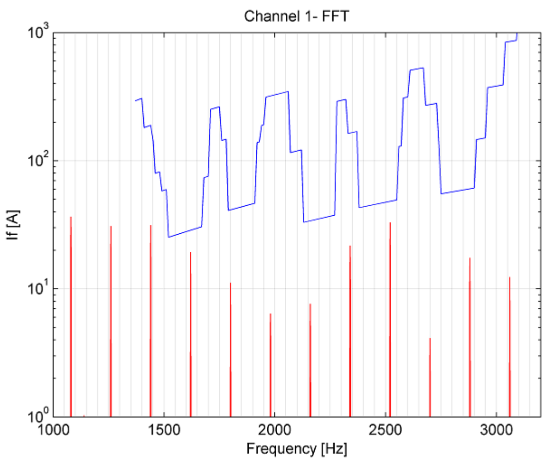


Fig. 3. I_f current harmonics with SHE modulation M=0.7, U_{DC}=3400V.

To prove the advantage of SHE over different modulation techniques the SPWM technique was implemented for the same operating point of the model.

Fig. 4 present I_f current harmonics and it can be observed that for SPWM technique current harmonics exceeded assumed limits.

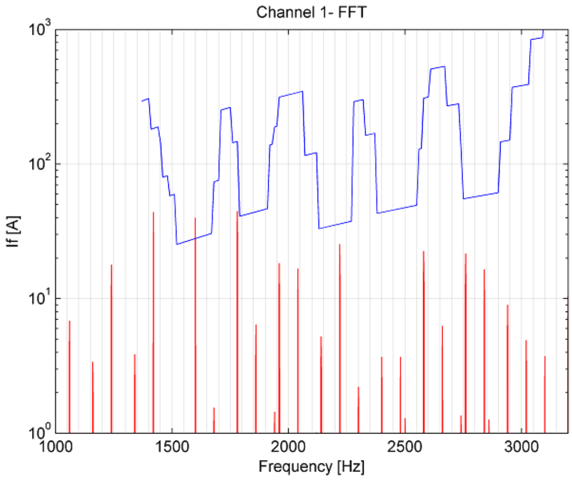


Fig. 4. I_f current harmonics with SPWM modulation M=0.7, U_{DC}=3400V.

6 Simulation results for three-level inverter

In this section the simulation results for three-level NPC inverter will be presented. In the first place the SHE strategy will be the same for all values of supplying voltage U_{DC}, only modulation index will be changed to keep constant value of VSI's output voltage basic component U_{out} = 1200V to keep traction drive in the same operating point. That means 5th, 7th, 11th and 13th voltage harmonics will be eliminated and modulation index will change according to values from Table 2.

Table 2. Modulation index correction regarding U_{DC} variations.

	U_{DC} [V]	**M [-]**	**V_{out} voltage harmonics [-]**			
			5^{th}	**7^{th}**	**11^{th}**	**13^{th}**
OP1	3600	0.66	0	0	0	0
OP2	3400	0.70	0	0	0	0
OP3	3200	0.75	0	0	0	0
OP4	3000	0.80	0	0	0	0
OP5	2800	0.85	0	0	0	0
OP6	2600	0.92	0	0	0	0
OP7	2400	1.00	0	0	0	0

Fig. 5 presents the values of I_f current harmonics for U_{DC} values from Table 2. It can be observed that for points describes in Table 2 as OP4, OP5, OP6 limits 'lim/8' are exceeded by harmonic 1620 Hz. The conclusion is: for this point, correction of control strategy is required.

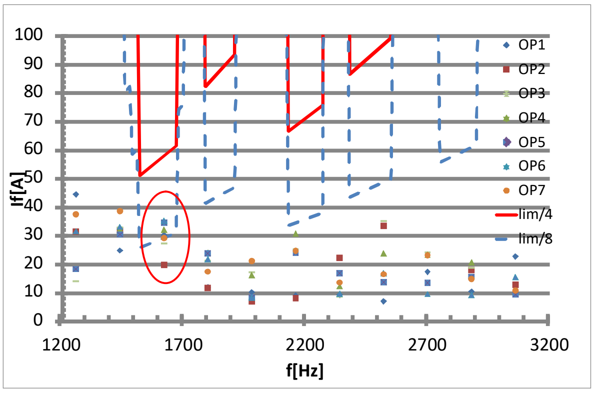


Fig. 5. I_f current harmonics for different values of U_{DC} and modulation index M (Table 2)-for three-level inverter.

For cases where limits were exceeded the SHE strategy was replaced by SHM with suitable values of mitigated harmonics. The pattern of harmonics control is presented in Table 3. Fig. 6 presents I_f current harmonics for U_{DC} values from Table 3 with revised control strategy to meet limits 'lim/8'.

Table 3. Revised voltage harmonics control strategy.

	U_{DC} [V]	M [-]	V_{out} voltage harmonics [-]			
			5th	7th	11th	13th
OP1	3600	0.66	0	0	0	0
OP2	3400	0.70	0	0	0	0
OP3	3200	0.75	0	0	0	0
OP4	3000	0.80	0	0	0.11	0.13
OP5	2800	0.85	0	0	0.11	0.13
OP6	2600	0.92	0	0	0.11	0.15
OP7	2400	1.00	0	0	0	0

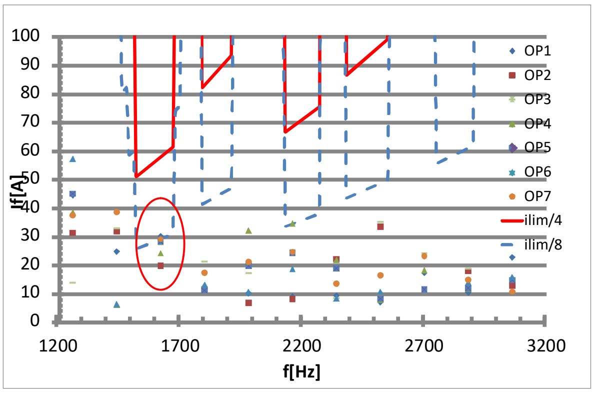


Fig. 6. I_f current harmonics for different values of U_{DC} and modulation index M (table 3))-for three-level inverter.

The following conclusion can be formulated: for chosen operating point of traction inverter the combination of SHE and SHM techniques can provide positive results in full range of supply voltage U_{DC}. Increasing of chosen voltage harmonics in SHM technique brings disadvantage in the form of increased THD of motor phase current and what follows increment of losses. The change of THD is presented in Fig. 7. It can be observer that maximum THD increment is 0.4 % for point OP4 and OP6, and it is relatively low in comparison to the benefits of meeting the compatibility requirements.

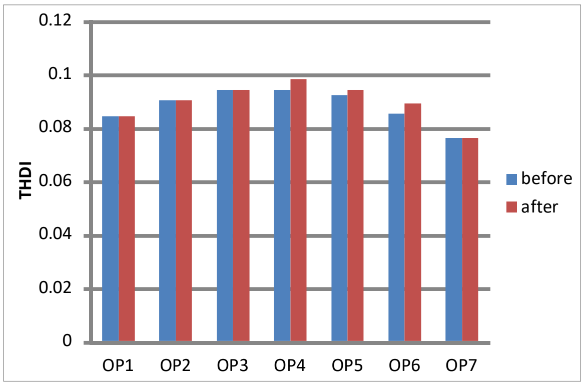


Fig. 7. THD I 'before' and 'after' revision of voltage harmonics control strategy for three-level inverter.

7 Simulation results for two-level inverter

In this section the results for two-level inverter will be presented. The approach to the problem will be similar to that presented in Section 6. Firstly the inverter's operating points from Table 4 will be analysed, taking into account the change of the supply voltage U_{DC} without correction of the harmonic elimination strategy. The results from this stage of work are presented in Fig. 8. It can be observed that current harmonic of 2160 Hz frequency exceeds the assumed limits for most operating points that were taken under consideration.

Table 4. Modulation index correction regarding U_{DC} variations

	U_{DC} [V]	M [-]	U_{out} voltage harmonics [-]			
			5th	7th	11th	13th
OP1	3600	0.66	0	0	0	0
OP2	3400	0.70	0	0	0	0
OP3	3200	0.75	0	0	0	0
OP4	3000	0.80	0	0	0	0
OP5	2800	0.85	0	0	0	0
OP6	2600	0.92	0	0	0	0
OP7	2400	1.00	0	0	0	0

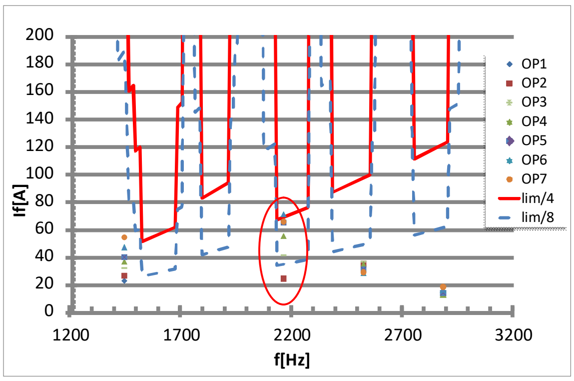


Fig. 8. I_f current harmonics for different values of U_{DC} and modulation index M (Table 4)-for two-level inverter.

The second step is to adjust the strategy of harmonics control to prevent exceeding the limits. The new strategy is described in Table 5. Fig. 9 presents that assumed limits are not exceeded using revised strategy.

Table 5. Revised voltage harmonics control strategy.

	U_{DC} [V]	M [-]	U_{out} voltage harmonics [-]			
			5th	7th	11th	13th
OP1	3600	0.66	0	0	0	0
OP2	3400	0.70	0	0	0	0
OP3	3200	0.75	0	0.1	0	0
OP4	3000	0.80	0	0.1	0	0.15
OP5	2800	0.85	0	0.1	0	0.1
OP6	2600	0.92	0	0.1	0	0.22
OP7	2400	1.00	0	0.1	0	0.1

The disadvantage of this method is negative impact on motor phase current THD (Fig. 10). The THD increase can reach even 2%. That means the losses in motor will increase as well. However the compatibility issues have priority, thus the proposed method is effective and ready for implementation in traction drives.

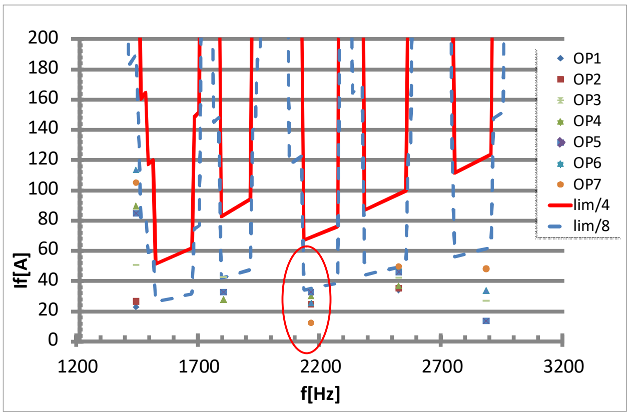


Fig. 9. I_f current harmonics for different values of U_{DC} and modulation index M (table 5))-for two-level inverter.

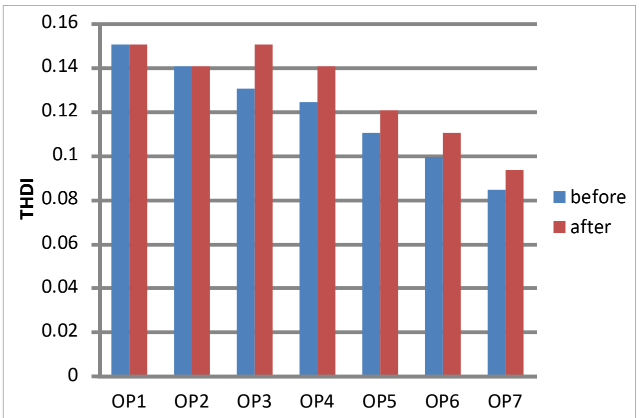


Fig. 10. THD I 'before' and 'after' revision of voltage harmonics control strategy for two-level inverter.

8 Conclusions

The variations of supplying voltage is a usual phenomenon in the electric traction power supply system. It is essential to take it under consideration during development of new traction drive control strategy. In this paper the Author presented the example of suggested corrections which must be implemented in SHE and SHM techniques to compensate the effect of DC voltage changes in traction drives. It was presented that using of proposed techniques it is possible to find solution which fulfil assumed restrictions regarding current harmonics in full range of DC voltage variations. The analysis were provided for both: two and three-level traction VSI. For every operating point of the VSI the different values of the supplying voltage must be taken under consideration. It is time consuming process but calculations are provided offline only once and implemented for whole lifetime of the drive. Presented work will be essential input in developing fully functional traction drive system based on SHE and SHM techniques.

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