Voltage Quality Comparison of Space Vector PWM Voltage Source Multilevel Inverter under Symmetric and Nonsymmetric Switching Sequence Variants: Voltage Harmonics Integral Factors

Lopatkin N.N.
Mathematics, physics and informatics department
The Shukshin Altai State Humanities Pedagogical University (ASHPU)
Biysk, Russia
nikolay_lopatkin@mail.ru

Zinoviev G.S.
Electronics and Electrical engineering department
Novosibirsk State Technical University (NSTU)
Novosibirsk, Russia
zinoviev@ref.nstu.ru

***Abstract*—The comparisons of the new offered optimum three-segment and the previously considered five-segment variants of the space vectors switching sequence are continued in values of the first three orders of the n-order integral voltage harmonics factors and in values of the first three orders of some unified indices, the so-called n-order aggregate switchings and integrated voltage harmonics factors. The corresponding dependencies on the amplitude modulation index are presented. The simulation results have proved the clear superiority of the new offered three-segment sequence in the main aggregate index values. The offered voltage source multilevel inverter space vector PWM algorithm of two delta voltages with the optimum three-segment vectors switching sequence variant can find industrial application due to its simplicity.**

Keywords—multilevel voltage source inverter; voltage space vector PWM (SVPWM) of two delta voltages; three-segment vectors switching sequence; quarter-wave symmetry; THD, n-order integral voltage harmonics factors, n-order aggregate switchings and integrated voltage harmonics factors

I. Introduction

The paper [1] offers the simple voltage source multilevel inverter space vector PWM algorithm (based on the oblique-angled coordinates of two delta voltages) with the optimum three-segment vectors switching sequence variant providing the instantaneous output voltage quarter-wave symmetry. The voltage waveforms, spectra and THD comparisons are performed under the same the lowest frequency modulation index values for the before offered nonconventional symmetric five-segment variant and the new offered nonsymmetric three-segment variant of the vectors switching sequence.

The above mentioned five-segment switching sequence variant in conjunction with the simple space vector algorithm provides the quite high output power quality [2-4], but it has disadvantages in both the output voltage quality and the quantity of the switchings per output voltage cycle in comparison with the conventional five-segment variant [5, 6].

The new offered three-segment variant absolute superiority in the THD values compared the considered symmetric five-segment variant has been proved for the full range of the amplitude modulation index values at any considered frequency modulation index values [1].

However, the supplementary investigation is needed to estimate the integral factors of voltage harmonics, which are defining the load current quality, in particular its THD value.

II. Problem Definition

The accurate estimation of the inverter output voltage quality contributes to the achievement of the necessary balance between the level of the harmonics component (within the acceptable range), the level of the dynamic losses in switches (and the corresponding value of the efficiency factor) and the specific (per output power) cost price of the modern multilevel voltage source inverter (MLVSI). The classical voltage THD, i.e. the factor of voltage harmonics K_{hu}, can provide the adequate valuation of the response harmonic contents only for the circuit with the pure active load. So the more fine voltage waveform analysis is needed compared to the analysis provided by the conventional THD and the appropriate standard means.

Developed by one of the authors of this paper in NETI (now NSTU), Novosibirsk, the advanced and general factors of harmonics have now been existing for over 30 years; these are the integral factors of harmonics (IHF) and the differential factors of harmonics (DHF) [7-14], which reflect the load filtering effect on the investigated voltage or current signals. These IHF and DHF are closely related to the algebraization of the differential equations (ADE) method which exists in numerous single-purpose variants. The ADE allows finding asymptotically with the preset accuracy the closed analytical form expressions for the mathematical relations between the voltage and current RMS values, using the coefficients of the integral-differential equation without its solving [8-10]. Since the MLVSI load usually has the inductive type of the reactance

978-1-5090-5648-417$31.00

(for instance, an induction motor), the voltage IHF should be considered.

The various orders IHF makes weighted (by the harmonic number) summation of harmonics, as a matter of fact, modeling the effect of the amplitude-frequency characteristic action of the corresponding order idealized electric integrating circuit. Such the ideal filter passes the fundamental harmonic without the magnitude reducing and reduces the magnitudes of the other harmonics by the number of times equal to the harmonic order number raised to the filter order power.

Similar to the THD definitions, the n-order voltage IHF, $\overline{K}_{hu}^{(n)}$, are calculated as follows [7-10]:

$$\overline{K}_{hu}^{(n)} = \frac{\overline{U}_{(hh)}^{(n)}}{\overline{U}_{(1)}^{(n)}} = \frac{\overline{U}_{(hh)}^{(n)} \cdot \omega^n}{U_{(1)}}, \quad (1)$$

$$\overline{K}_{hu}^{(n)} = \frac{\sqrt{\left(\overline{U}^{(n)}\right)^2 - \left(\overline{U}_{(1)}^{(n)}\right)^2}}{U_{(1)}/\omega^n} = \sqrt{\left(\frac{\overline{U}^{(n)} \cdot \omega^n}{U_{(1)}}\right)^2 - 1}, \quad (2)$$

$$\overline{K}_{hu}^{(n)} = \frac{\sqrt{\left(\overline{U}_{(hh)}^{(n)}\right)^2}}{U_{(1)}/\omega^n} = \sqrt{\sum_{k=2}^{\infty}\left(\frac{U_{(k)}}{k^n \cdot U_{(1)}}\right)^2}, \quad (3)$$

here $U_{(k)}$, $\overline{U}_{(1)}^{(n)}$, $\overline{U}_{(hh)}^{(n)}$ and $\overline{U}^{(n)}$ are the RMS value of the voltage *k* harmonic component and RMS values of the results of the n-fold indefinite integral taking of the instantaneous values of the fundamental component $\overline{u}_{(1)}^{(n)}$, of the high harmonics component $\overline{u}_{(hh)}^{(n)}$ and of the whole voltage $\overline{u}^{(n)}$, correspondingly; ω is the angular frequency of the fundamental component. Since the process without a DC component is being considered,

$$\overline{u}^{(n)} = \overline{u}_{(1)}^{(n)} + \overline{u}_{(hh)}^{(n)}. \quad (4)$$

The n-order DHF corresponds to the n-fold derivation of the above-mentioned instantaneous values, so they are calculated according to (1)…(3) for $n < 0$. The classical voltage THD (factor of harmonics, FH, K_{hu}) corresponds to $n = 0$.

The weighted THD (WTHD) factor (that is completely corresponding to the first order IHF $\overline{K}_{hu}^{(1)}$) is also used now for the current waveform estimation in many foreign researches with various kinds of publications, as in [15-19]. The well-known USA authors of [5] (using it, probably, since about 2000) along with the basic weighted THD, have also developed the system of the weighted THD factors for the induction motor load with the frequency-dependent parameters.

The purpose of this paper is to complete the comparison of the two above mentioned variants of the vectors switching sequence by considering the first to third orders IHF as the prior load current quality indicators.

III. Integral Factors of Harmonics Comparison

A. Direct Integral Factors of Harmonics Comparison and Switchings Number

To obtain the continuous curves of the dependences of the output voltage first to third orders IHF on the amplitude modulation index m_a, the Mathcad spectrum model has been used. The amplitude modulation index is determined by

$$m_a = \sqrt{3} \cdot U / U_d, \quad (5)$$

here U and U_d are the values of the reference space vector magnitude and the input direct voltage of the unit level, respectively.

The corresponding IHF curves for the five-segment and the three-segment switching sequences under the frequency modulation index m_f values 12, 18, 24, and 30 are shown in Fig. 1…Fig. 3. Here

$$m_f = f_c / f, \quad (6)$$

f_c and f are, respectively, clock and modulating frequencies.

As can be seen, the three-segment sequence has the advantage in the first order IHF values at the lowest frequency modulation index values (m_f = 12, 18, see Fig. 1, a)). In the rest of cases the five-segment sequence results turned out to be better. The more the m_f value is and the more the IHF order value is, the less IHF values of the five-segment sequence are.

But the price that is to be paid with regards to the switches commutation frequency might be too high (see the corresponding waveform of the phase-to-ground voltage in [1]). So, let's consider the switchings (commutations) number in the MLVSI phase leg per the output voltage cycle N_{swph} as the important in itself index defining the switching losses value of the MLVSI and strongly dependent on the frequency modulation index value. As can be seen in Fig. 4, the N_{swph} value of the five-segment switching sequence is at least 1.6 times that of the three-segment switching sequence.

Obviously, the final decision in favour of one of the being compared switching sequence variants needs the consideration of some aggregate index, which takes into account both the voltage quality and the price of its achieving. Such the index will be described in the next subsection.

The number of the switchings N_{swph} can also be used for estimated calculation of the n-order voltage (or current) IHF approximately expressed in terms of the zero-order IHF, i.e. the factor of harmonics, K_{hu} (THD):

$$\overline{K}_{hu}^{(n)} \approx \frac{K_{hu}}{\left(N_{swph}\right)^n}. \quad (7)$$

The semi logarithmic plots of the zero to third orders output voltage IHF for m_f = 12, m_f = 18 under the using of the being compared five-segment and three-segment sequences are shown in Fig. 5 a), Fig. 6 a) and Fig. 5 b), Fig. 6 b), respectively. The solid and dash lines correspond to calculation according to (3) and (7), respectively.

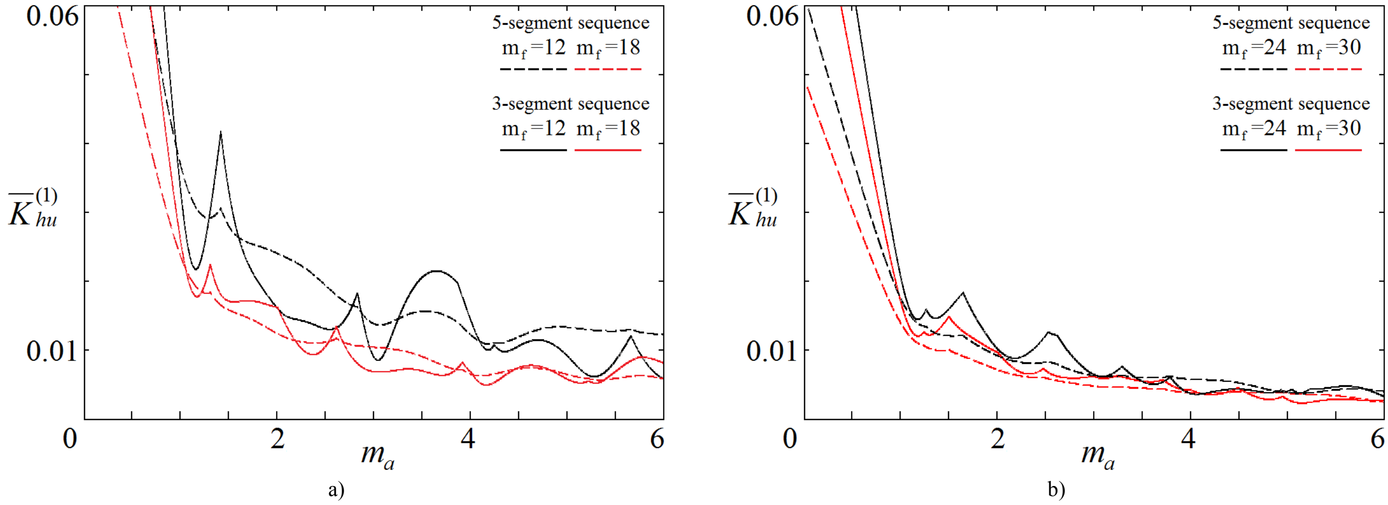


Fig. 1. The first order integral voltage harmonics factor Mathcad simulation results for the five-segment and the three-segment switching sequences: a) under m_f = 12 and m_f = 18; b) under m_f = 24 and m_f = 30.

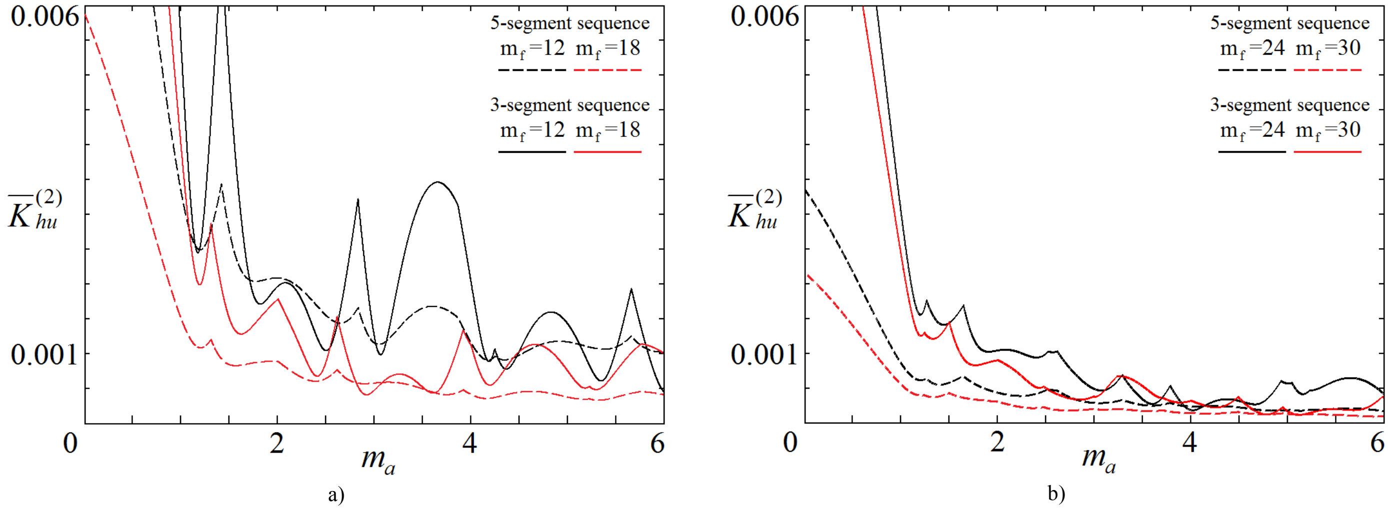


Fig. 2. The second order integral voltage harmonics factor Mathcad simulation results for the five-segment and the three-segment switching sequences: a) under m_f = 12 and m_f = 18; b) under m_f = 24 and m_f = 30.

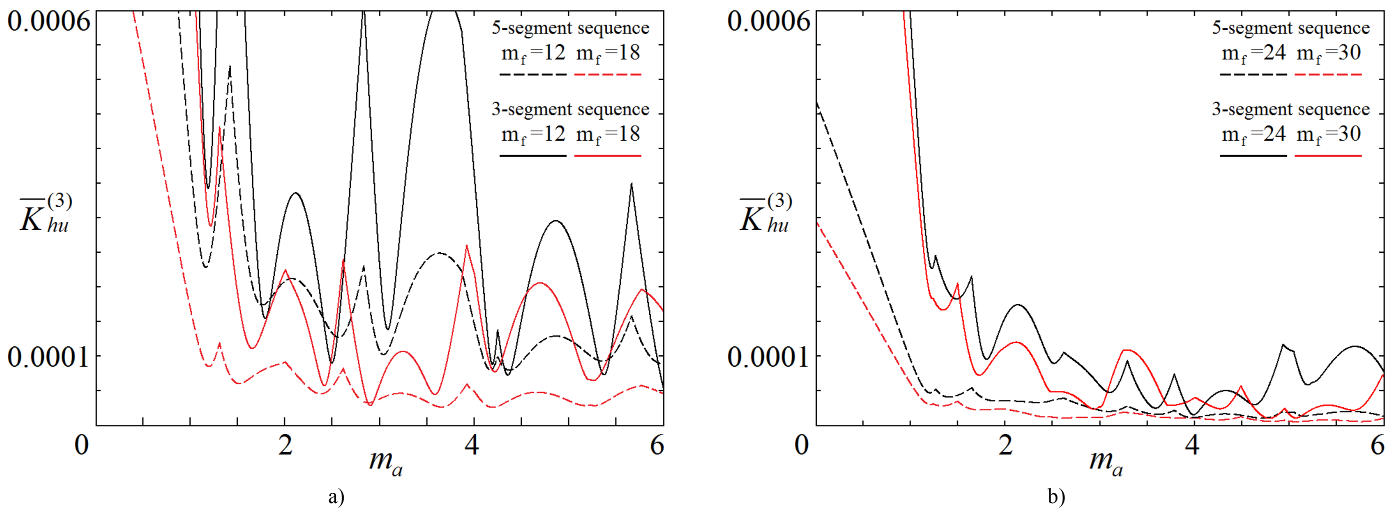
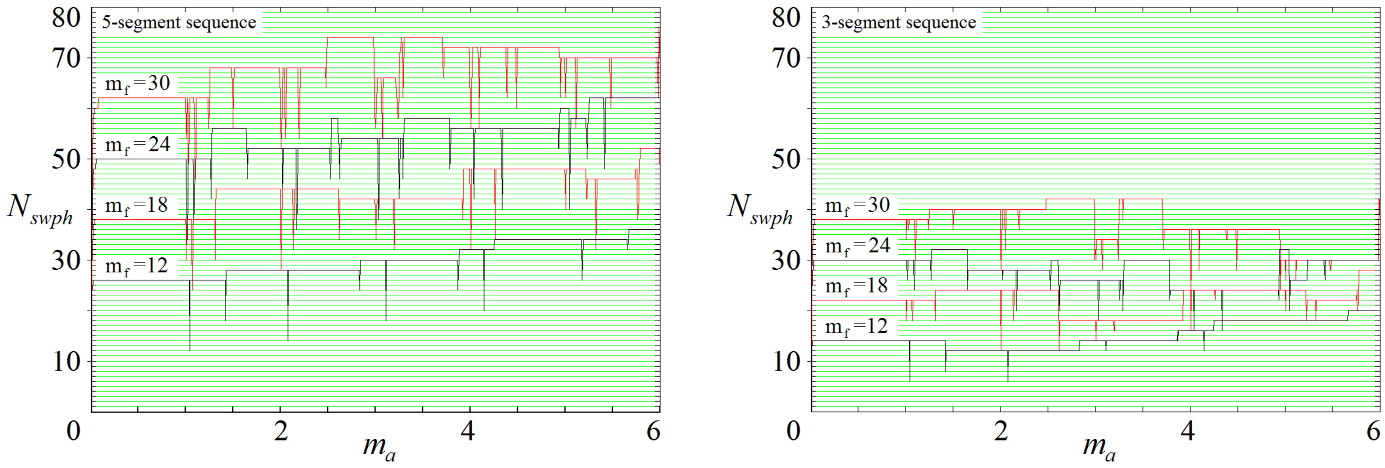
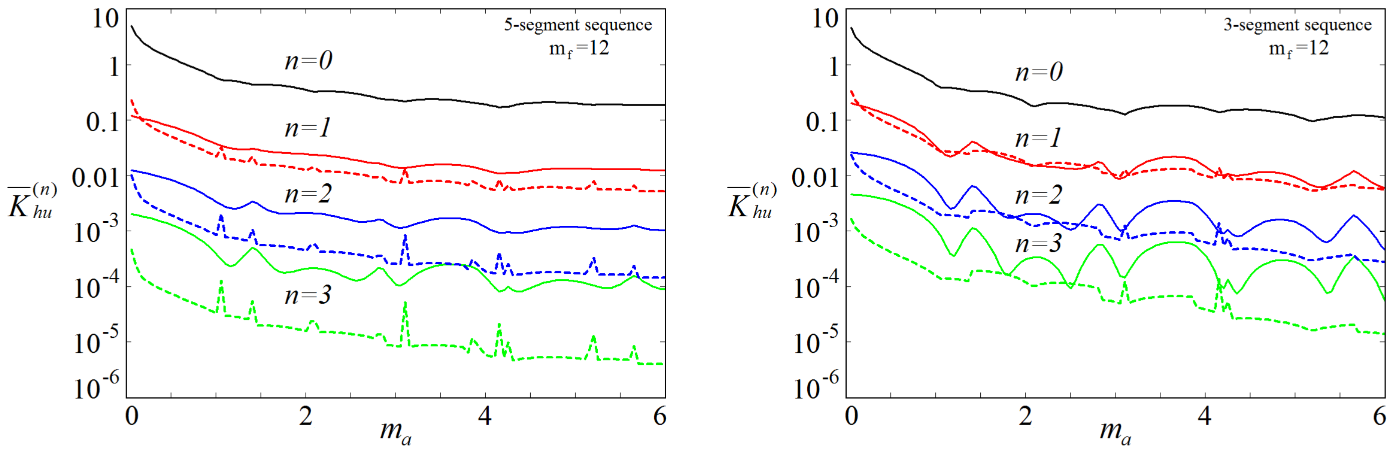


Fig. 3. The third order voltage integral harmonics factor Mathcad simulation results for the five-segment and the three-segment switching sequences: a) under m_f = 12 and m_f = 18; b) under m_f = 24 and m_f = 30.



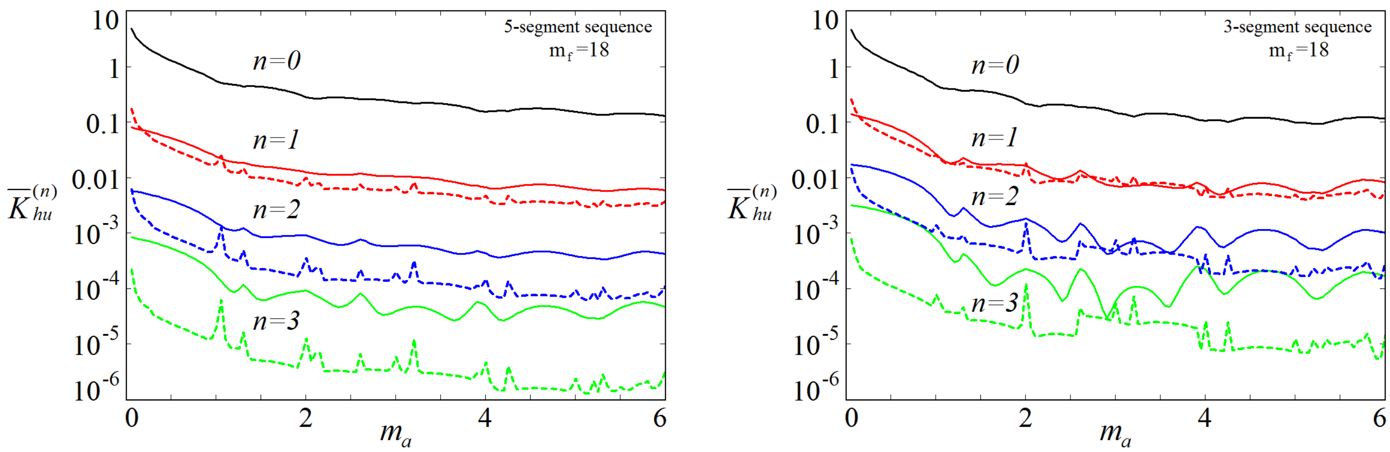
a) b)

Fig. 4. The Mathcad simulation results of the inverter phase leg switchings numbers: a) for the five-segment switching sequence; b) for the three-segment switching sequence.



a) b)

Fig. 5. The Mathcad simulation results of the zero to third orders voltage integral harmonics factors under $m_f = 12$ a) for the five-segment switching sequence; b) for the three-segment switching sequence.



a) b)

Fig. 6. The Mathcad simulation results of the zero to third orders voltage integral harmonics factors under $m_f = 18$ a) for the five-segment switching sequence; b) for the three-segment switching sequence.

As can be seen, (7) produces underestimated IHF values. The minimum error (difference between (3) and (7) results) is obtained for $n = 1$, i.e. for the weighted THD which is the second most important (after the THD) index. The more the n number value is, the more the corresponding error is.

B. Aggregate Switchings and Integrated Voltage Harmonics Factors

References [20, 8] were the first to propose the aggregate indices taking into account both the voltage harmonics and the number of the switchings in the MLVSI phase leg per the output voltage cycle N_{swph}.

The later paper [21] presents somewhat different indices, the so-called normalized integral (weighted) harmonic factors of n-th order of the output voltage:

$$\overline{K}^{(n)}_{hu\_norm} = \left(N_{swph}\right)^n \cdot \overline{K}^{(n)}_{hu}. \quad (8)$$

These normalized indices eliminate the IHF dependence on the frequency modulation index, and they should depend only on the amplitude modulation index. Such the coefficients are helpful and suitable for the group harmonics consideration, and they are used now by many researchers [22, 23]. But due to (7) all these reduced integral harmonic factors add up to the level of the zero order IHF (THD):

$$\overline{K}^{(n)}_{hu\_norm} \approx \overline{K}^{(0)}_{hu} = K_{hu}. \quad (9)$$

Obviously, the switchings number has not been counted for the THD itself (see (8) for $n = 0$).

It seems to make sense to use the singlefold multiplying of the IHF by the switchings number for any n value, so let's here define the n-order aggregate switchings and integrated voltage harmonics factors (ASIHF) as follows:

$$\overline{K}^{(n)}_{hu-aggr-sw} = N_{swph} \cdot \overline{K}^{(n)}_{hu}. \quad (10)$$

The estimated ASIHF calculation can be performed by using the approximation, similar to (7):

$$\overline{K}^{(n)}_{hu-aggr-sw} \approx \frac{\overline{K}^{(0)}_{hu-aggr-sw}}{\left(N_{swph}\right)^n} = \frac{N_{swph} \cdot K_{hu}}{\left(N_{swph}\right)^n} = \frac{K_{hu}}{\left(N_{swph}\right)^{n-1}}. \quad (11)$$

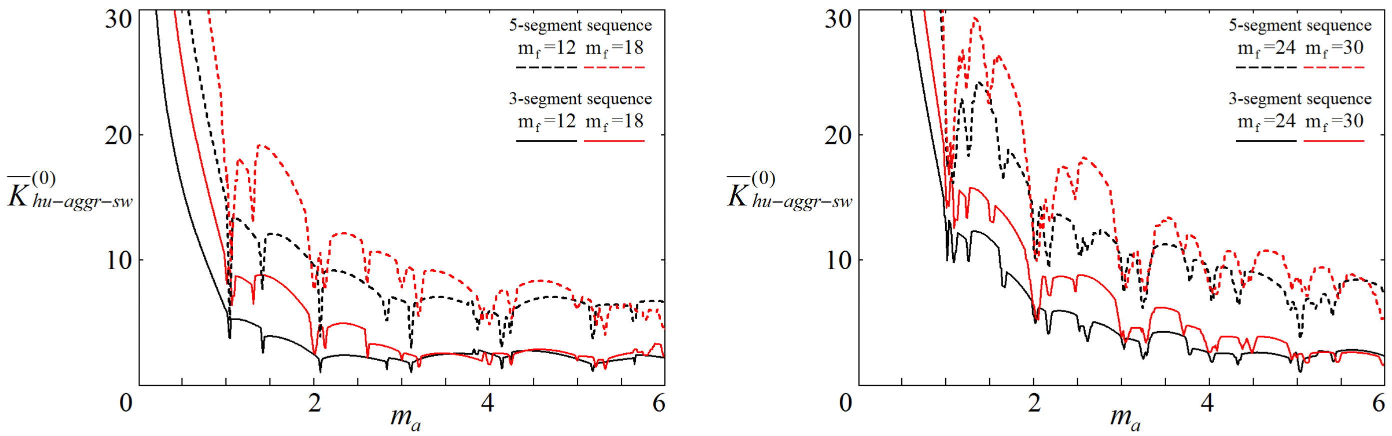
Processing the weighted THD (the first order IHF) produces the same values for the first order normalized integral harmonic factor and the first order aggregate switchings and integrated voltage harmonics factor:

$$\overline{K}^{(1)}_{hu-aggr-sw} = \overline{K}^{(1)}_{hu\_norm} = N_{swph} \cdot \overline{K}^{(1)}_{hu}. \quad (12)$$

The zero to third orders ASIHF curves for the five-segment and the three-segment switching sequences under the frequency modulation index m_f values 12, 18, 24, and 30 are shown in Fig. 7…Fig. 10.

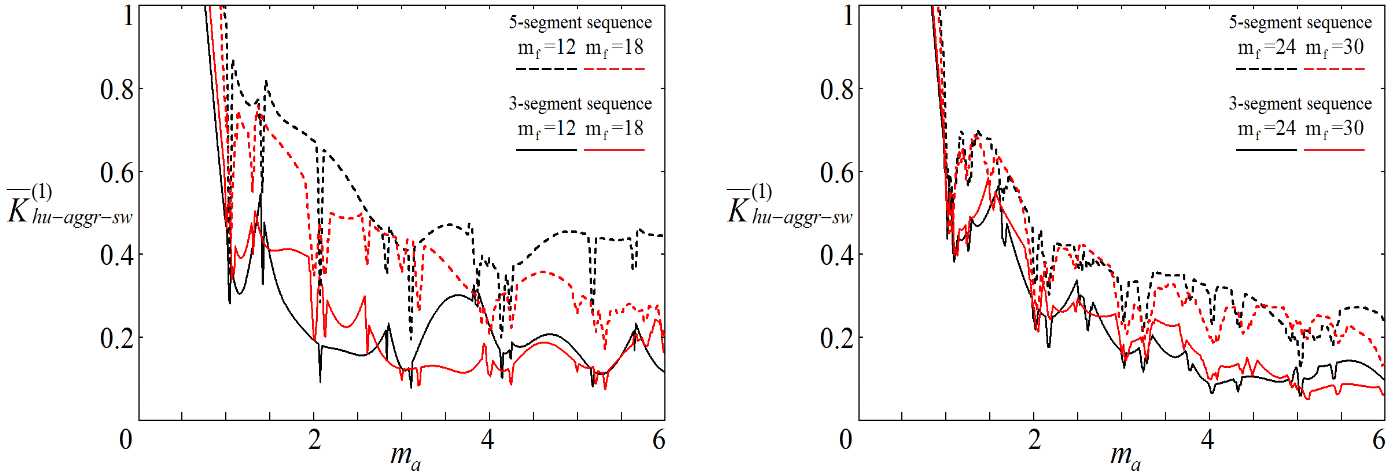
The zero order ASIHF corresponds to the THD, and similar to the THD curves [1], the advantages of the three-segment sequence variant are obvious for the all considered m_f values. But, unlike the tendencies of the THD values curves, the zero order ASIHF values demonstrate in Fig. 7 the approaching to one another and the fusion of their dependences on m_a curves as m_a is increased for the both considered switching sequences and for the all considered m_f values. The least value of the frequency modulation index ($m_f = 12$) produces the least values of the zero order ASIHF. As a rule, the more the m_f value is, the more zero order ASIHF values are.

Beginning from the first order ASIHF their values become the ambiguous functions both the amplitude and the frequency modulation indices. Nevertheless, the new offered three-segment variant absolute superiority in the first order ASIHF values compared the considered symmetric five-segment variant has been proved for the full range of the amplitude modulation index values at any considered frequency modulation index values.



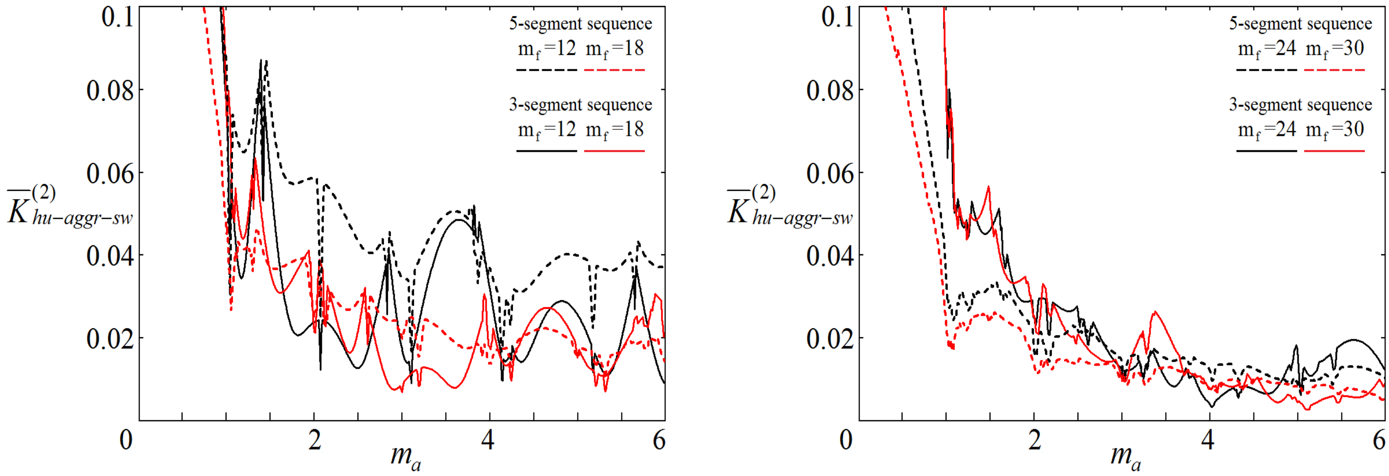
a) b)

Fig. 7. The zero order aggregate switchings and integrated voltage harmonics factor Mathcad simulation results for the five-segment and the three-segment switching sequences: a) under m_f = 12 and m_f = 18; b) under m_f = 24 and m_f = 30.



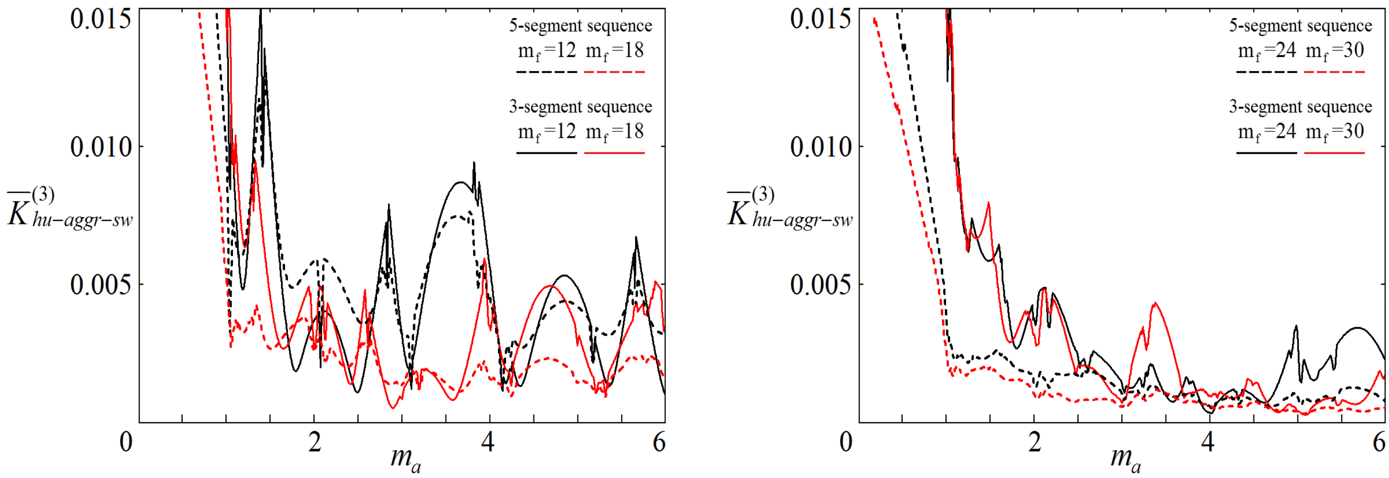
a) b)

Fig. 8. The first order aggregate switchings and integrated voltage harmonics factor Mathcad simulation results for the five-segment and the three-segment switching sequences: a) under $m_f = 12$ and $m_f = 18$; b) under $m_f = 24$ and $m_f = 30$.



a) b)

Fig. 9. The second order aggregate switchings and integrated voltage harmonics factor Mathcad simulation results for the five-segment and the three-segment switching sequences: a) under $m_f = 12$ and $m_f = 18$; b) under $m_f = 24$ and $m_f = 30$.



a) b)

Fig. 10. The third order aggregate switchings and integrated voltage harmonics factor Mathcad simulation results for the five-segment and the three-segment switching sequences: a) under $m_f = 12$ and $m_f = 18$; b) under $m_f = 24$ and $m_f = 30$.

The five-segment variant has the advantages in the second order ASIHF values for the low amplitude modulation index values and in the third order ASIHF values for almost the full range of the amplitude modulation index values. However, due to the proportion (7) of the initial IHF coefficients, the more the order ASIHF is, the less values of this ASIHF and its contribution to the corresponding current THD are.

IV. Conclusions

The n-order integral voltage harmonics factors are considered and the new n-order aggregate switchings and integrated voltage harmonics factors are described for the comparisons of the new offered optimum three-segment and the before considered five-segment variants of the space vectors switching sequence. These aggregate factors should be treated as the supplementary instrumentation for the comparison of the multilevel inverter (or any AC voltage generating system, based on the power electronics converters) output voltage modulation algorithms which takes into account both the voltage quality and the price of its achieving. They must be further studied to be correlated with the total power losses and the efficiency factor of the entire multilevel inverter circuit, including the output filter.

The advantages of the new offered nonsymmetric three-segment switching sequence variant in the main aggregate index values, namely, the values of the zero and first orders aggregate switchings and integrated voltage harmonics factors, have been proved by the Mathcad simulation. The supplementary comparison with one of the conventional switching sequence variant, close in the switching quantity, is desirable.

The offered voltage source multilevel inverter space vector PWM algorithm of two delta voltages is applicable to any arbitrary circuit of the voltage source multilevel inverter with any arbitrary number of the equal feeding DC voltage levels.

This algorithm, together with the optimum three-segment vectors switching sequence variant, can find industrial application due to its simplicity. The algorithm implementation can be performed with using a cheap DSP.

References

[1] N.N. Lopatkin, “Voltage quality comparison of space vector PWM voltage source multilevel inverter under symmetric and nonsymmetric switching sequence variants: voltage waveforms, spectra and THD,” in press.

[2] N.N. Lopatkin, “Simple delta voltages space vector PWM algorithm for voltage source multilevel inverters,” in Proc. 2016 2-nd International Conference on Intelligent Energy and Power Systems (IEPS), Kyiv, Ukraine, 2016, pp. 149-154.

[3] N.N. Lopatkin, “Output voltage simulation of multilevel inverter with space vector modulation of two delta voltages,” Technical Electrodynamics, is. 5, pp. 20-22, 2016.

[4] N.N. Lopatkin, “Voltage harmonics integral factors estimation of multilevel inverter with space vector modulation of two delta voltages,” in Proc. 13th International Conference on Actual Problems of Electronic Instrument Engineering, vol. 1, Novosibirsk, 2016, part 3, pp. 112-115.

[5] D.G. Holms, T.A. Lipo, Pulse Width Modulation for Power Converters, NJ: IEEE Press, 2003.

[6] Bin Wu, M. Narimani, High-Power Converters and AC Drives, Wiley-IEEE Press, 2017.

[7] G.S. Zinovyev, Efficiency Criteria of Energy Processes in Valve Converters, Kiev: Preprint 342 of Institute of Electrodynamics of Academy of Sciences of the Ukrainian SSR, 1983.

[8] G.S. Zinovyev, Direct Methods of Calculation of Power Indicators of Valve Converters, Novosibirsk: NSU, 1990.

[9] G.S. Zinoviev, Power Electronics, Moscow: Jurajt, 2012.

[10] G.S. Zinoviev, “The results of solving some problems of electromagnetic compatibility of valve converters,” Electrical Engineering, is. 11, pp. 12-16, 2000.

[11] G.S. Zinovyev, Electromagnetic Compatibility of Power Electronics Devices (Electric Power Aspect), Novosibirsk: NSTU, 1998.

[12] V.A. Lipko, G.S. Zinoviev, “The family of extended power quality factors,” in Proc. EDM’2015, 16-th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices (EDM), Erlagol, Altai, 2015, pp. 553-556.

[13] N.N. Lopatkin, Y.A. Chernov, “Virtual instrument for nonconventional total harmonic distortion factors evaluation,” in Proc. SIBCON-2016, 2016 International Siberian Conference on Control and Communications (SIBCON), Russia, Moscow, 2016.

[14] N.N. Lopatkin, Y.A. Chernov, “Differential and integral factors of harmonics LabVIEW estimation,” in Proc. EDM’2016, 17th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices (EDM), Erlagol, Altai, 2016, pp. 493-498.

[15] V. Oleschuk, V. Ermuratskii, F. Barrero, “Analysis and synthesis of symmetrical output voltage of three-level converters with space-vector PWM,” Technical Electrodynamics, is. 5, pp. 17-19, 2016.

[16] A.R. Beig, S. Kanukollu, K. Al Hosani, A. Dekka, “Space-vector-based synchronized three-level discontinuous PWM for medium-voltage high-power VSI,” IEEE Transactions on Industrial Electronics, vol. 61, is. 8, pp. 3891-3901, 2014.

[17] W. Chen, H. Sun, X. Gu, and C. Xia, “Synchronized space vector PWM for three level VSI with lower harmonic distortion and switching frequency,” IEEE Transactions on Power Electronics, vol. 31, is. 9, pp. 6428-6441, 2016.

[18] V. Karthikeyan, and V. Jamuna, “Hybrid control strategy for BCD topology based modular multilevel inverter,” Circuits and Systems, is. 7, pp. 1441-1454, 2016. [Online]. Availaible: http://dx.doi.org/10.4236/cs.2016.78126

[19] A. Tripathi, and G. Narayanan, “Investigations on optimal pulse width modulation to minimize total harmonic distortion in the line current,” IEEE Transactions on Industry Applications, vol. 53, is. 1, pp. 212-221, 2017.

[20] I.A. Bakhovtsev, G.S. Zinoviev, “Energy conversion quality analysis of PWM autonomous voltage inverter,” Power thyristor converters, Interuniversity collection of scientific papers, edition of Novosibirsk Institute of Electrical Engineering (NETI), pp. 3-12, 1987.

[21] I.A. Bakhovtsev, G.S. Zinoviev, “Generalized analysis of output power of multiphase multilevel PWM voltage source inverters,” Electricity,is. 4, pp. 26-33, 2016.

[22] R.L. Gorbunov, D.V. Makarov, “An input filter design technique for an AC switching converter,” Science Bulletin of the NSTU, Novosibirsk, vol. 60, is. 3, pp. 94-112, 2015.

[23] R.L. Gorbunov, G.I. Poskonnyy, “Experimental verification of the simplified mathematical model for harmonic distortion analysis in AC buck converter,” in Proc. EDM’2016, 17th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices (EDM), Erlagol, Altai, 2016, pp. 433-440.