Assessment of Output Voltage Quality of Three-Phase Multilevel Inverter with Nearest Vector Selecting Space Vector Control

Nikolay N. Lopatkin, *Member*, *IEEE*
Shukshin Altai State Humanities Pedagogical University (ASHPU), Biysk, Russia

Abstract – **The paper presents the nearest vector selecting space vector control (SVC) of any arbitrary MLVSI circuit with any arbitrary number of the equal feeding DC voltage levels. The linear mode LabVIEW model for the SVC digital controller is designed in two variants of the reference signals sampling. The MLVSI output voltage THD and integrated voltage harmonics factors (IHF), needed for computing of the load circuit voltages and currents and their quality indices, are estimated as functions of the sampling frequency index).**

Index Terms – **Multilevel inverter, voltage space vector control (SVC), integer and fractional parts of delta voltages relative values, n-order integrated voltage harmonics factors (IHF), LabVIEW simulation.**

I. INTRODUCTION

THE SIGNIFICANT progress has been achieved in inverters output voltage and power increasing mostly due to the multilevel voltage source inverters (MLVSI) [1]-[6].

Since the high MLVSI levels number makes it possible to avoid high switching frequency PWM while providing high output voltage quality, the so-called pseudo-modulation techniques [7] becomes the most promising for industrial applications. In particular, the space vector control (SVC) with the nearest vector selecting [8], [9] may be convenient modulation technique for present and future industrial medium and high voltage adjustable speed drive converters with enough high number of levels.

The new nearest vector selecting algorithm has been developed in the context of the space vector algorithm of two delta voltages [10]-[13] which uses barycentric and affine (oblique-angled) coordinates on triangles of three nearest vectors to the reference one [14]. The offered technique uses both the integer parts and the fractional parts of the reference delta voltages relative values as the coordinates of the reference voltage space vector. This approach to the SVC for any arbitrary MLVSI circuit with any arbitrary number of the equal feeding DC voltage levels needs no preliminary finding of anything coefficients and holding them in look-up tables [15].

II. PROBLEM DEFINITION

The thorough research has been accomplished to estimate the THD and the integrated voltage harmonics factors (IHF) of the resulting MLVSI voltage for the nearest vector selecting SVC [16] in its continuous variant. This case of the analog control might be treated as digital control with the tending to zero sampling period duration, and it shows the boundaries of voltage quality for this kind of SVC upon non-zero sampling period, in particular THD and IHF exact hypothetical lower limits.

The above mentioned IHF factors of various orders were offered by Professor G.S. Zinoviev (NETI, now NSTU, Novosibirsk) more than 30 years ago, and they produces weighted (by the harmonic number) summation of harmonics, thereby modeling the effect of the amplitude-frequency characteristic action of the corresponding order idealized electric integrating circuit [17]. The n-order voltage IHF can be defined as follows:

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

where for estimated voltage u values $U_{(k)}$ and $\overline{U}_{(hh)}^{(n)}$ are the RMS value of the k harmonic component and RMS value of the result of the n-fold indefinite integral taking of the instantaneous value of the high harmonics component $\overline{u}_{(hh)}^{(n)}$, correspondingly; ω is the angular frequency of the fundamental component. The block diagram of the used LabVIEW virtual instrument for the assessment of simulated signals integrated harmonics factors and THD (the IHF-meter) and the IHF clear and concise description, which is concerning their values obtaining and application, are given in [18], [19] and [16].

The purpose of this paper is to provide the MLVSI output voltages quality estimate while the reference voltages sampling is impacting on them. Here we will confine ourselves to consideration of the two variants of the reference sinusoidal signals sampling under few phase voltage amplitude modulation index values.

978-1-5386-7054-5/18/$31.00 ©2018 IEEE

III. LABVIEW SVC DIGITAL CONTROLLER MODEL

The The LabVIEW SVC digital controller model with the two versions of the quantized reference signals builder is presented in Fig. 1. The SVC controller is intended for any three-phase MLVSI with any arbitrary levels number N under linear mode, i.e. under the condition that the equal feeding DC voltage levels are physically available in sufficient numbers.

Each of the two waveforms builders of the sampled reference delta voltages u^*_{REFSbc} and u^*_{REFSab} (Fig. 1, a and b) has the input control elements to specify the desirable values of the output frequency f_{out}, the sampling frequency index (or the sample rate) m_{fs} and the phase voltage amplitude modulation index m_{aY}. Here the sampling frequency index has been introduced by analogy with PWM frequency modulation index,

$$m_{fs} = f_s / f_{out}, \qquad (2)$$

f_s is the sampling frequency; the phase amplitude modulation index is defined as follows:

$$m_{aY} = U / U_d = U^*, \qquad (3)$$

where U is the value of the reference voltage space vector magnitude, equal to the reference phase voltage amplitude, U_d is the input DC voltage of the unity (base) level. Throughout the paper, all the voltages marked with an asterisk (*) are the corresponding relative values, in relation to U_d.

The difference between the two variants of the quantized reference signals builder is demonstrated in Fig. 2 and Fig. 3 for $m_{aY} = 3.14$. The illustrating figures are shown here for a comparatively low value of the sampling frequency index, $m_{fs} = 42$ ($f_s = 2100$ Hz for $f_{out} = 50$ Hz). The sampling is supposed to be performed for the midpoint of each the cycle.

The sampling cycle number time-dependent function $k(t)$ of Fig. 1,a is shown in Fig. 2,a and corresponds to the equation

$$k(\omega t) = \left\lfloor \left(\frac{\omega t}{2\pi} - \left\lfloor \frac{\omega t}{2\pi} \right\rfloor \right) \cdot m_{fs} \right\rfloor + 1, \qquad (4)$$

where $\lfloor w \rfloor$ is the integer part of w, i.e. the rounding down w to the closest integer number, taking into account the sign (the "floor" function).

The respective sampled reference voltage u^*_{REFSbc} is shown in Fig. 2,b and is described as follows:

$$u^*_{REFSbc}(\omega t) = m_{aY} \cdot \sqrt{3} \cdot \sin\left(\frac{2\pi \cdot k(\omega t) - \pi}{m_{fs}} \right). \qquad (5)$$

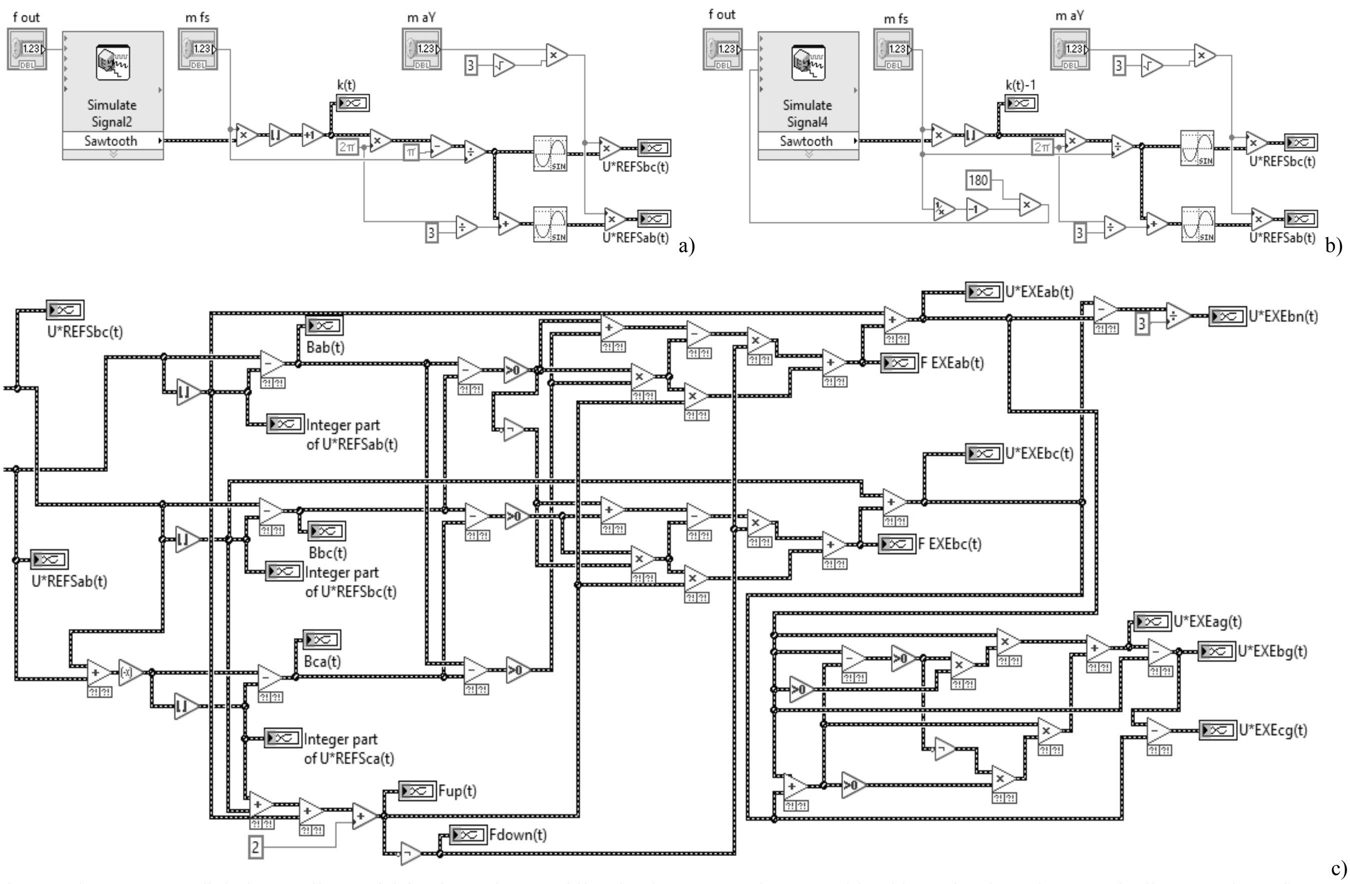

Fig. 1. LabVIEW SVC digital controller model for three-phase multilevel voltage source inverter with arbitrary level number N under linear mode: a) first version of quantized reference signals builder; b) second version of quantized reference signals builder; c) core part of SVC controller.

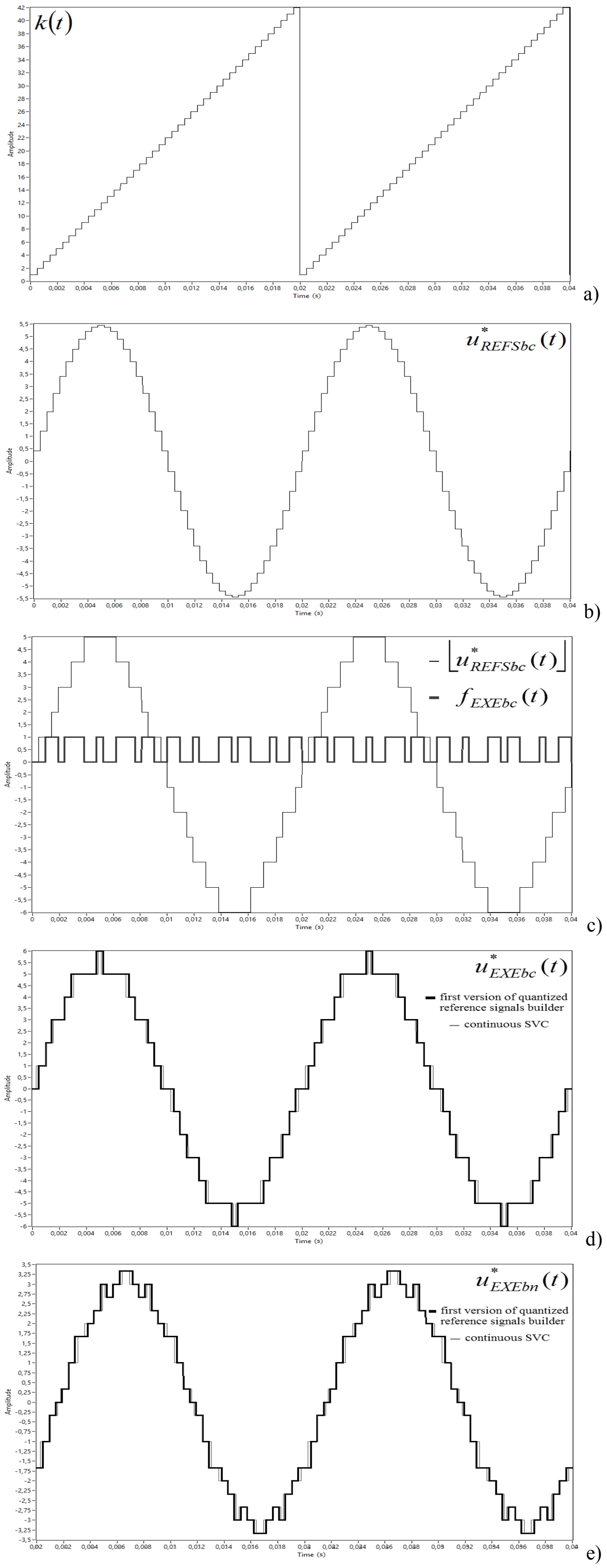

Fig. 2. LabVIEW-simulated digital SVC controller signals waveforms for first variant of quantized reference signals builder under m_{aY} = 3.14, m_{fs} = 42: a) sampling cycle number time-dependent function, b) sampled reference delta voltage, c) executed delta voltage components, d) executed delta voltage, e) executed phase-to-neutral voltage.

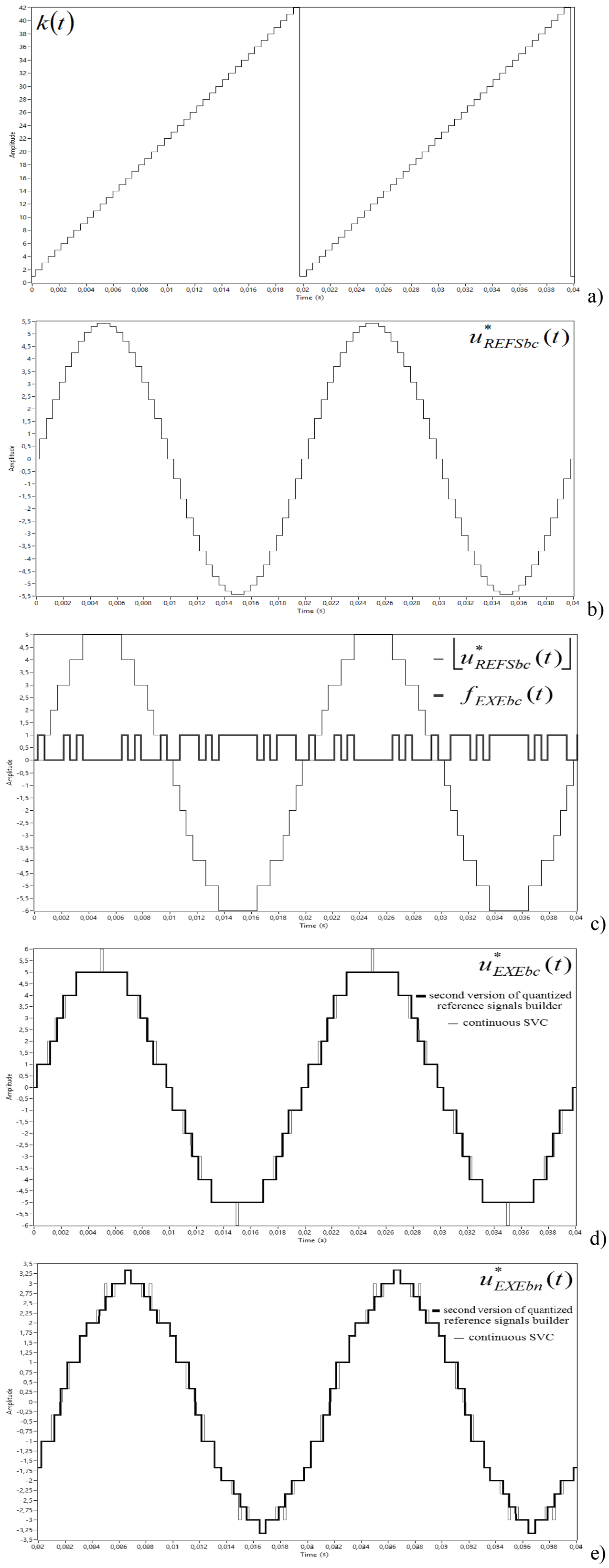

Fig. 3. LabVIEW-simulated digital SVC controller signals waveforms for second variant of quantized reference signals builder under m_{aY} = 3.14, m_{fs} = 42: a) sampling cycle number time-dependent function, b) sampled reference delta voltage, c) executed delta voltage components, d) executed delta voltage, e) executed phase-to-neutral voltage.

The same cycle number function $k(t)$ of Fig. 1,b is shown in Fig. 3,a and corresponds to the equation

$$k(\omega t)=\left\lfloor\left(\frac{\omega t+\pi/m_{fs}}{2\pi}-\left\lfloor\frac{\omega t+\pi/m_{fs}}{2\pi}\right\rfloor\right)\cdot m_{fs}\right\rfloor+1; \quad (6)$$

the respective sampled reference voltage u^*_{REFSbc} is shown in Fig. 3,b and is described by equation

$$u^*_{REFSbc}(\omega t)=m_{aY}\cdot\sqrt{3}\cdot\sin\left(\frac{2\pi\cdot(k(\omega t)-1)}{m_{fs}}\right). \quad (7)$$

So, the first sampled value for $k(\omega t)=1$ generates the sampled reference voltage u^*_{REFSbc} waveform with the quarter-wave symmetry but having different behavior at $\omega t=0$: the waveform just is jumping from some negative to some positive value in case of the first variant of the quantized reference signals builder (see Fig. 2, b), and the waveform has the zero value level for the second variant (see Fig. 3, b).

The core part of SVC controller (Fig. 1, c) has replicated the respective Matlab/Simulink model [15] and has already been used [16].

The main used in [10]-[13], [15] the delta voltage two-component formation principle is kept in the offered approach (see Fig. 2, c and Fig. 3, c):

$$u^*_{EXEgh}(t)=\left\lfloor u^*_{REFSgh}(t)\right\rfloor+f_{EXEgh}(t), \quad (8)$$

where the relative value of the being executed output delta voltage $u^*_{EXEgh}(t)$ and its two components are instantaneous functions of current time, the relative value of the sampled reference delta voltage $u^*_{REFSgh}(t)$ and its integer part $\left\lfloor u^*_{REFSgh}(t)\right\rfloor$ are here both the stepped functions, and $f_{EXEgh}(t)$ is the pulse function that can possess only the values 0 and 1 (see [15]).

As can be seen from Fig. 2, d and Fig. 3, d as well as from Fig. 2, e and Fig. 3, e, the resulting executed delta and phase-to-neutral voltages can be quite different for the two variants of the quantized reference signals builder, so the quantitive study of harmonic factors for some m_{aY} range is needed.

IV. Simulation Results

The LabVIEW-simulated curves of the MLVSI output voltage THD (K_{hu}) and first to third orders IHF indices ($\overline{K}^{(n)}_{hu}$ for n = 1…3) dependences on the sampling frequency index are presented in Fig. 4 for the two variants of the quantized reference signals builder. Here the sampling frequency index values are assigned as follows:

$$m_{fs}=6\cdot(2k-1),\ k\in N,\ k\le 50, \quad (9)$$

namely, m_{fs} = 6; 18; 30;…594.

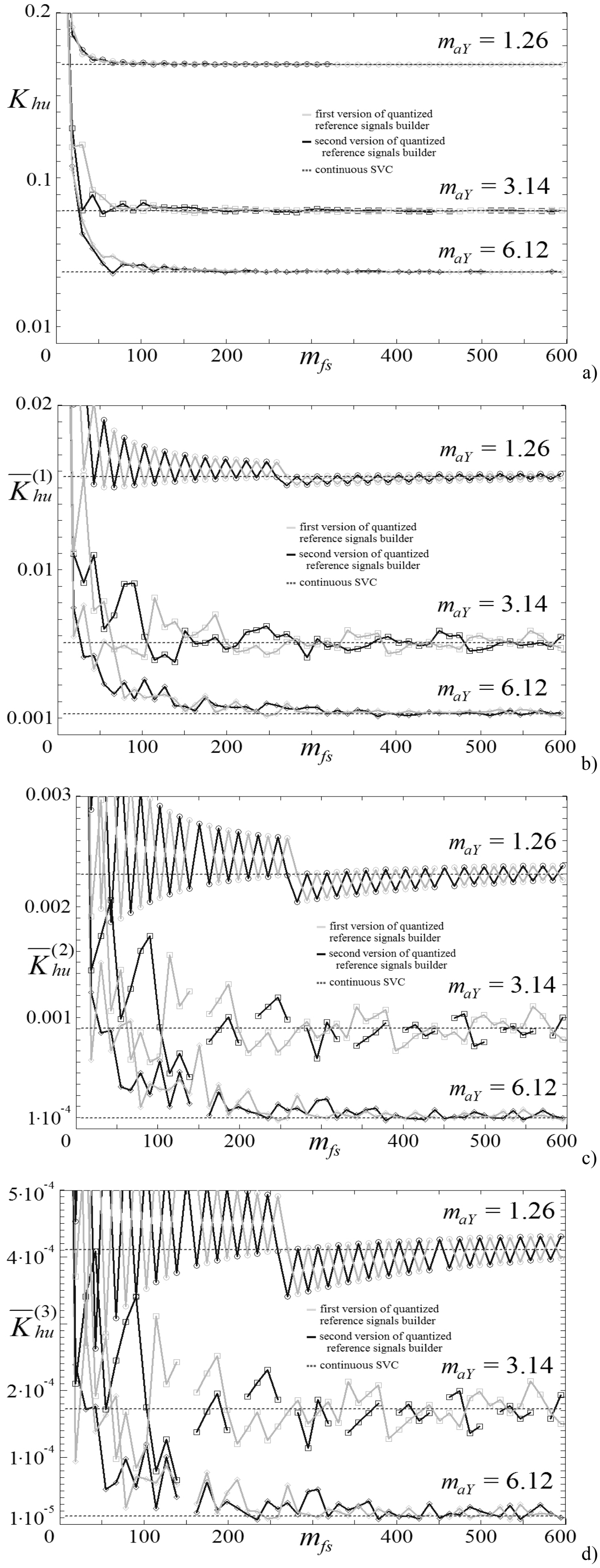

Fig. 4. LabVIEW-simulated THD (a) and first three orders IHF (b, c and d) dependences on the sampling frequency index m_{fs} for the two variants of the reference sinusoidal signals sampling under phase voltage amplitude modulation index m_{aY} values 1.26, 3.14 and 6.12.

The points in Fig. 4, c and d, where the IHF-meter results have been distorted a lot due to the mean values poor elimination and the consequent wrong values of the twice and thrice integrated high harmonics component signal, have been removed.

As can be seen from Fig. 4, the higher the IHF order is, the higher the relative difference values between the results of the continuous SVC and the results obtained through the reference sinusoidal signals samplings under the comparatively low values of the sample rate are. The two variants of the reference sinusoidal signals sampling compete with each other, having their advantages on successive sub-ranges of the sampling frequency index.

Beginning from some not very high m_{fs} value the resulting output voltage waveforms of the both sampling variants come close to the respective continuous SVC waveform. The rising and falling edges positions are still changing, whereas the quantity of the steps (and levels) and appropriate MLVSI semiconductor devices switchings number, power losses and efficiency remain unchanged.

The numeric data on the values of the delta voltage IHF indices for those same selected phase voltage amplitude modulation index m_{aY} values (1.26, 3.14 and 6.12) under three m_{fs} values (594, 1050 and 2106) are placed in Table I. Here the respective sampling period values, corresponding to equation

$$T_s = \frac{1}{f_s} = \frac{1}{f_{out} \cdot m_{fs}}, \tag{10}$$

are 33.7, 19.0 and 9.5 μs for f_{out} = 50 Hz.

As can be noted, the harmonic content of the resulting output voltage under the digital SVC can be both some better and some worse compared to the continuous SVC results. The minus sign of the relative difference corresponds to each case when the IHF value under digital SVC is less than the respective continuous SVC value.

Because the continuous SVC doesn't provide the THD and IHF indices exact hypothetical lower limits, one can choose the first or the second sampling variant on the basis of the convenient combination of the output voltage and current quality and the computational effort.

Thus, freed up microprocessor computing resources can be directed to processing of other data needing the more fast response (some close-loop control process), equipment diagnostics etc.

The MLVSI output voltage zero to third orders IHF values dependences on the phase voltage amplitude modulation index, obtained with m_{aY} step equal to 0.1 for m_{fs} = 2106, show the almost perfectly matching of the three curves, corresponding to the continuous SVC [16] and the offered first and second digital control versions.

TABLE I
MLVSI OUTPUT VOLTAGE ZERO TO THIRD ORDERS IHF VALUES

Control parameters			Harmonic distortion factors							
Phase amplitude modulation index m_{aY}	SVC type		Total harmonic distortion		First order IHF		Second order IHF		Third order IHF	
			$\overline{K}_{hu}^{(0)} = K_{hu}$	Relative difference, %	$\overline{K}_{hu}^{(1)}$	Relative difference, %	$\overline{K}_{hu}^{(2)}$	Relative difference, %	$\overline{K}_{hu}^{(3)}$	Relative difference, %
1.26	Continuous SVC		0.168545478476	Reference values	0.0156516	Reference values	0.00229402	Reference values	0.000410701	Reference values
3.14			0.08005172801897		0.00557263		0.000905254		0.000172267	
6.12			0.04297928868022		0.00124104		$9.33371 \cdot 10^{-5}$		$1.17979 \cdot 10^{-5}$	
	Digital SVC									
	m_{fs}	Sampling version								
1.26	594	First	0.1685921795594	0.028	0.0155368	-0.733	0.00224511	-2.132	0.000397773	-3.148
		Second	0.168562837729	0.010	0.0158566	1.310	0.00237453	3.510	0.000431322	5.021
	1050	First	0.1685755016019	0.018	0.0157453	0.599	0.0023306	1.595	0.000420116	2.292
		Second	0.1685576909653	0.007	0.015559	-0.592	0.00225558	-1.676	0.000400596	-2.460
	2106	First	0.1685444948277	-0.0006	0.0156905	0.249	0.00230975	0.686	0.000414783	0.994
		Second	0.1685511336482	0.003	0.0155952	-0.360	0.00227081	-1.012	0.00040462	-1.481
3.14	594	First	0.08034833064616	0.371	0.00525211	-5.752	0.00080445	-11.135	0.000150248	-12.782
		Second	0.08030508472647	0.316	0.00594045	6.600	0.00100288	10.784	0.000193258	12.185
	1050	First	0.08006783183935	0.020	0.00554331	-0.526	0.000901308	-0.436	0.000171946	-0.186
		Second	0.07991167002516	-0.175	0.00575464	3.266	0.000950793	5.031	0.000181122	5.140
	2106	First	0.08003706167006	-0.018	0.00574116	3.024	0.000951101	5.065	0.000181962	5.628
		Second	0.0800637600696	0.015	0.00553381	-0.697	0.000892399	-1.420	0.000169269	-1.740
6.12	594	First	0.0431100254879	0.304	0.00114584	-7.671	$8.20884 \cdot 10^{-5}$	-12.052	$1.05187 \cdot 10^{-5}$	-10.843
		Second	0.04295165208329	-0.064	0.00129807	4.595	$9.36154 \cdot 10^{-5}$	0.298	$9.9086 \cdot 10^{-6}$	-16.014
	1050	First	0.04290933884246	-0.163	0.00124815	0.573	$8.84255 \cdot 10^{-5}$	-5.262	$9.36313 \cdot 10^{-6}$	-20.637
		Second	0.04304862937807	0.161	0.00130852	5.437	0.000128814	38.009	$2.15247 \cdot 10^{-5}$	82.445
	2106	First	0.04300843038659	0.068	0.00122182	-1.549	$8.42402 \cdot 10^{-5}$	-9.746	$8.78956 \cdot 10^{-6}$	-25.499
		Second	0.04299999011319	0.048	0.00126862	2.222	0.000104895	12.383	$1.50046 \cdot 10^{-5}$	27.180

V. CONCLUSIONS

The digital implementation of the space vector control algorithm with the nearest vector selection for the three-phase arbitrary MLVSI circuit with any arbitrary number N of the equal feeding DC voltage levels is tested by LabVIEW simulation. The offered space vector control technique uses both the integer part and the fractional part of the reference delta voltages relative values as the coordinates of the reference voltage space vector and needs no preliminary finding of anything coefficients and holding them in look-up tables.

The two variants of the reference sinusoidal signals sampling has been considered. The impact of the reference voltages sample rate on the SVC output voltages quality is assessed.

The offered approach and the obtained curves of the zero to third orders IHF indices dependences on the sampling frequency index can be interesting and helpful to industrial engineers who designs some system “MLVSI - filter - load circuit” for particular load circuit parameters values and uses the SVC technique.

The sampling frequency reduction makes it possible to provide the room for manoeuvre within the existing computing resources budget while keeping the most important for the concrete task weighted THD (IHF) values within some acceptable limits.

REFERENCES

[1] Rodriguez J., Lai J.-S., Peng F.Z. Multilevel inverters: a survey of topologies, controls, and applications // IEEE Transactions on Industrial Electronics, Vol. 49, Iss. 4, August 2002, pp. 724-738.

[2] Kouro S., Malinowski M., Gopakumar K., Pou J., Franquelo L.G., Wu Bin, Rodriguez J., Pérez M.A., and Leon J.I. Recent advances and industrial applications of multilevel converters // IEEE Transactions on Industrial Electronics, Vol. 57, Iss. 8, Aug. 2010, pp. 2553-2580.

[3] Gonzalez S.A., Verne S.A., Valla M.I. Multilevel Converters for Industrial Applications. CRC Press, 2013.

[4] Luo F.L., Ye H. Advanced DC/AC Inverters: Applications in Renewable Energy. CRC Press, 2013.

[5] Ge B., Peng F.Z., and Li Y. Multilevel Converter/Inverter Topologies and Applications, Chapter 14 in Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications, First Edition. Wiley-IEEE Press, 2014. Edited by H. Abu-Rub, M. Malinowski and K. Al-Haddad, pp. 422-462.

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

[7] Leon J.I., Kouro S., Rodriguez J., Wu Bin. The essential role and the continuous evolution of modulation techniques for voltage-source inverters in the past, present, and future power electronics // IEEE Transactions on Industrial Electronics, Vol. 63, Iss. 5, May 2016, pp. 2688-2701.

[8] Rodriguez J., Moran L., Correa P., Silva C. A vector control technique for medium-voltage multilevel inverters // IEEE Transactions on Industrial Electronics, Vol. 49, Iss. 4, August 2002, pp. 882-888.

[9] Rodriguez J., Moran L., Pontt J., Correa P., Silva C. A high-performance vector control of an 11-level inverter // IEEE Transactions on Industrial Electronics, Vol. 50, Iss. 1, February 2003, pp. 80-85.

[10] Lopatkin N.N. Simple delta voltages space vector PWM algorithm for voltage source multilevel inverters // 2016 2-nd International Conference on Intelligent Energy and Power Systems (IEPS), Kyiv, Ukraine, June 7-11, 2016, Proceedings, pp. 149-154.

[11] Lopatkin N.N. Output voltage simulation of multilevel inverter with space vector modulation of two delta voltages // Tekhnichna Elektrodynamika (Technical Electrodynamics), edition of National Academy of Sciences of Ukraine, Kyiv, Iss. 5, 2016, pp. 20-22 (in Russian).

[12] Lopatkin N.N. Voltage quality comparison of space vector PWM voltage source multilevel inverter under symmetric and nonsymmetric switching sequence variants: voltage waveforms, spectra and THD // ICIEAM-2017, 2017 3rd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), IEEE Conference # 40534, Russia, St. Petersburg, Peter the Great Saint-Petersburg Polytechnic University, May 16-19, 2017, Proceedings, pp. 1-8.

[13] Lopatkin N.N. Simple space vector PWM scheme with quarter-wave symmetric output voltage waveform for three-phase multilevel inverter // 2017 International Multi-Conference on Engineering, Computer and Information Sciences (SIBIRCON), Russia, Novosibirsk, Novosibirsk Akademgorodok, September 18-24, 2017, Proceedings, pp. 433-438.

[14] Lopatkin N.N. Some new representations of the multilevel inverter voltage space vector in the complex plane // SIBCON-2015, 2015 International Siberian Conference on Control and Communications (SIBCON), Russia, Omsk, May 21-23, 2015, Proceedings, 222em.pdf (pp. 1-11).

[15] Lopatkin N.N. New implementation of nearest vector selecting space vector control for three-phase multilevel voltage source inverter // ICIEAM-2018, 2018 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), IEEE Conference # 43496, Russia, Moscow, Moscow Polytechnic University, May 15-18, 2018, Proceedings, paper 3.4.39 (pp. 1-7), in press.

[16] Lopatkin N.N. Voltage THD and integrated voltage harmonics factors of three-phase multilevel voltage source inverter with nearest vector selecting space vector control // ICIEAM-2018, 2018 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), IEEE Conference # 43496, Russia, Moscow, Moscow Polytechnic University, May 15-18, 2018, Proceedings, paper 3.4.40 (pp. 1-6), in press.

[17] Zinoviev G.S. Power Electronics. Textbook for undergraduate students. Fifth edition. Moscow: Jurajt, 2012. 667 p. (in Russian).

[18] Lopatkin N.N., Chernov Y.A. Virtual instrument for nonconventional total harmonic distortion factors evaluation // SIBCON-2016, 2016 International Siberian Conference on Control and Communications (SIBCON), Russia, Moscow, May 12-14, 2016. Proceedings, pp. 1-6.

[19] Lopatkin N.N., Chernov Y.A. Differential and integral factors of harmonics LabVIEW estimation // EDM’2016, 17th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices (EDM), Erlagol, Altai, 30 June - 4 July, 2016, Proceedings, pp. 493-498.

Lopatkin Nikolay Nikolaevich is the graduate of the industrial electronics department of the NETI (now NSTU), 1988, the candidate of engineering sciences, NSTU, 1998, the lecturer of the mathematics, physics and informatics department of Shukshin Altai State Humanities Pedagogical University (ASHPU), Biysk. His research interests include multilevel converters and control of them, quality indexes of electrical energy processes and improvement of them.
E-mail: nikolay_lopatkin@mail.ru