Aggregate Factors of Switchings and Integrated Voltage Harmonics of Three-Phase Multilevel Voltage Source 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 deals with the model of the nearest vector selecting space vector control (SVC) of any arbitrary MLVSI circuit with any arbitrary number of any equal feeding DC voltage levels. Using the LabVIEW simulation results for instantaneous SVC, the aggregate factors of switchings and integrated voltage harmonics (ASIHF) dependences on phase voltage amplitude modulation index are obtained and compared with the corresponding results of the quarter-wave symmetric space vector PWM (SVPWM).**

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), n-order aggregate switchings and integrated voltage harmonics factors (ASIHF).**

I. Introduction

The MULTILEVEL voltage source inverters (MLVSI) circuits and the techniques for control of them are the two wings, which provide now the rise of the medium and high voltage three-phase adjustable speed drives [1-6].

Notwithstanding the importance of the circuitry solutions, the modulation technique is their general resource belonging to every of the MLVSI circuits in some adapted form and making it possible to provide high quality output AC voltage and current, high output capability, low losses in power switches, low cost of components or acceptable combinations of the parameters values of the MLVSI.

The high MLVSI levels number avoided pulse width modulation (PWM) with too high switching frequency while providing high output voltage quality. Moreover, the so-called pseudo-modulation techniques [2] becomes the most promising for industrial applications. In particular, the space vector (SV) control (SVC) with the nearest vector selecting [7]-[10] may be convenient modulation technique for present and future industrial medium and high voltage adjustable speed drive converters with enough high number of levels. Originally, the SVC was described for cascaded multilevel inverter (CMLI) control [7]-[10], but obviously, it is equally attractive for use in a variety of MLVSI circuits, again, for the case of 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 [11]-[15] which uses barycentric and affine (oblique-angled) coordinates on triangles of three nearest vectors to the reference one [16]. 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 novel approach to the SVC for any arbitrary MLVSI circuit with any arbitrary number of the equal feeding dc voltage levels in itself needs no preliminary finding of anything coefficients and holding them in look-up tables [17].

The offered scheme applies no special operations radically different from used in the traditional one. But it utilizes the conventional space vector PWM (SVPWM) attribute, namely “modulating triangle” of the three vectors nearest to the reference voltage SV (NTV).

As have been shown in [16], the fractional parts of the reference delta voltages relative values are not only the duty cycles of the three nearest vectors NTV in SVPWM, but also the barycentric coordinates on corresponding triangle for the reference voltage SV endpoint. So, the closer to unity the fractional value of certain relative delta voltage is, the closer to the related vertex the reference voltage SV endpoint is. The highest value of the three barycentric coordinates on the NTV triangle points to the appropriate vertex as the vertex, closest to the reference point, and such a way one can choose the space vector nearest to the reference vector endpoint. Due to the fractional parts of the reference delta voltages relative values are mapped to the possible nearest vectors, the closest to the reference voltage space vector is being selected easily through the comparisons of the three fractional values for maximum value detection in one of the two triangles [17].

The main used in [11]-[15] delta voltage two-component formation principle is kept in the offered technique:

$$u^*_{EXExy}(t) = \lfloor u^*_{REFxy}(t) \rfloor + f_{EXExy}(t)\,, \qquad (1)$$

where the relative value of the being executed output delta voltage $u^*_{EXExy}(t)$ and its two components are instantaneous functions of current time, the stepped function $\lfloor u^*_{REFxy}(t) \rfloor$ is the integer part of the relative value of the reference delta voltage $u^*_{REFxy}(t)$ (all relative values are in relation to input dc voltage U_d of the unity level), and $f_{EXExy}(t)$ is the pulse function that can possess only the values 0 and 1.

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

II. PROBLEM DEFINITION

The controller LabVIEW model of the SVC instantaneous version [17] has been developed (see Fig. 1), and the simulated curves of the output voltage THD and first to third orders integrated harmonics factors (IHF) dependences on amplitude modulation index have been obtained [18]. The SVC controller replicates the respective Matlab/Simulink model [17], based on the above mentioned new delta voltages coordinates approach. The used IHF-meter (see Fig. 2) has proven before to be an enough reliable and precision simulation instrument [19], [20]. It implements one of the time-domain IHF definitions [21], which makes it possible to process directly the input signal high harmonics component u_{hh}.

The joint approach and attributes of the offered quarter-wave symmetric SVPWM [13]-[15] and SVC techniques have made to compare their THD and IHF simulated results for the lowest values of the SVPWM frequency modulation index. The SVC advantage in the THD values and drawback in the IHF indices values at some amplitude modulation index sub-ranges have been noted. Thus, the SVC and the quarter-wave symmetric SVPWM can compete against each other in the MLVSI load current quality issues.

Our preferences can be based on the taking into account the switching losses value of the MLVSI which is directly proportional to the switchings (commutations) number in the MLVSI phase leg per the output voltage cycle N_{swph}.

It seems reasonable that further study and comparison should consider the aggregate indices, which take into account both the voltage quality and the price of its achieving. This paper provides the so-called aggregate switchings and integrated voltage harmonics factors (ASIHF) dependences on amplitude modulation index in two sub-ranges, both for the SVC and the quarter-wave symmetric SVPWM and some their intercomparisons results.

III. AGGREGATE FACTORS OF SWITCHINGS AND INTEGRATED VOLTAGE HARMONICS

The considered here ASIHF indices have already been used for the SVPWM-controlled MLVSI output voltage assessment in a small amplitude modulation index range [14]. As we have noticed, issues [22] and [23] were the first to propose the aggregate indices taking into account both the voltage harmonics and the number N_{swph} of the per cycle switchings in the MLVSI phase leg output voltage.

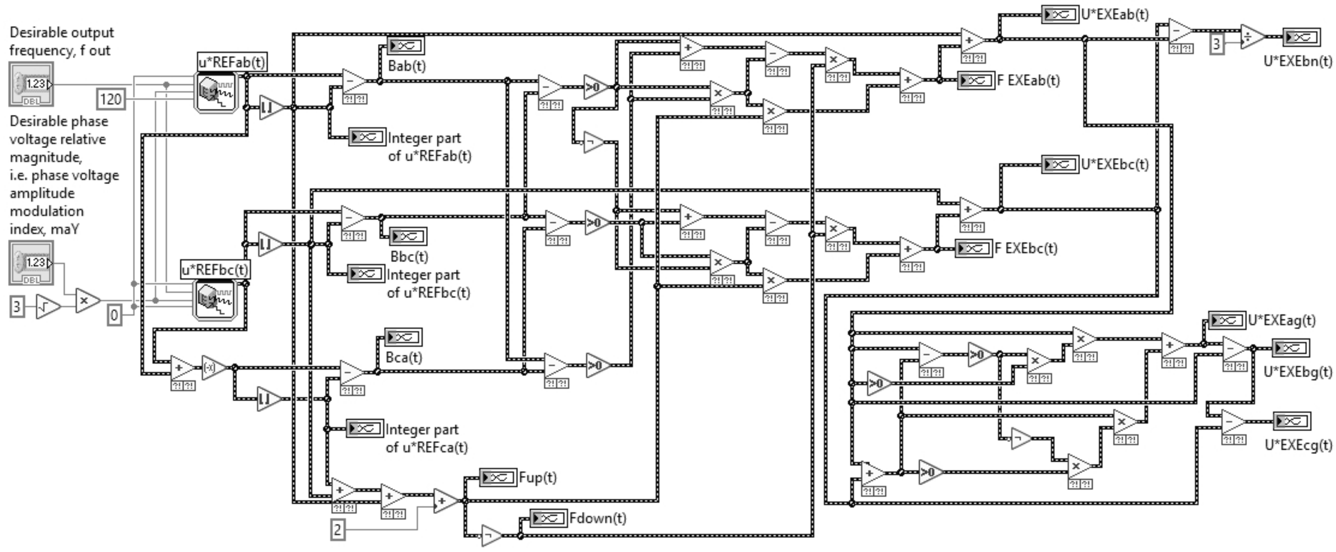

Fig. 1. LabVIEW "instantaneous SVC" controller model for three-phase multilevel voltage source inverter with arbitrary level number.

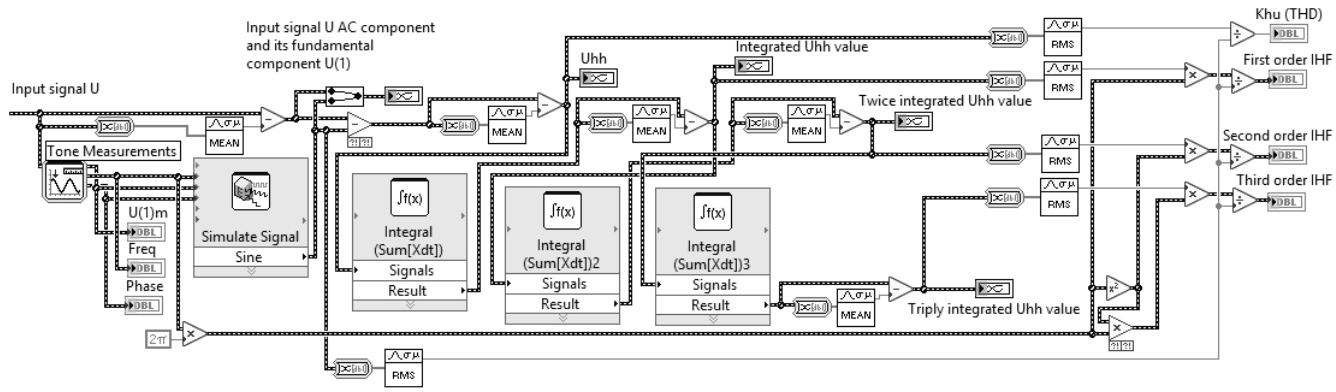

Fig. 2. LabVIEW virtual metering instrument for zero to third orders integrated harmonics factors assessment.

The most general n-th order aggregate switchings and integrated voltage harmonics factor has been defined with using the singlefold multiplying of the n-th order voltage IHF $\overline{K}^{(n)}_{hu}$ by the switchings number:

$$\overline{K}^{(n)}_{hu-aggr-sw} = N_{swph} \cdot \overline{K}^{(n)}_{hu} . \qquad (2)$$

The estimated n-th order ASIHF calculation can be performed by using the approximation as follows:

$$\overline{K}^{(n)}_{hu-aggr-sw} \approx \frac{\overline{K}^{(0)}_{hu-aggr-sw}}{(N_{swph})^{n}} = \frac{N_{swph} \cdot K_{hu}}{(N_{swph})^{n}} = \frac{K_{hu}}{(N_{swph})^{n-1}} , \qquad (3)$$

where K_{hu} is harmonics factor (THD).

The comparatively recent paper [24] presents a rather different output voltage index, the so-called normalized integral (weighted) harmonic factor of n-th order:

$$\overline{K}^{(n)}_{hu\_norm} = (N_{swph})^{n} \cdot \overline{K}^{(n)}_{hu} . \qquad (4)$$

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 now frequently used in the design of filters. But due to analog of left part of (3) for $\overline{K}^{(n)}_{hu}$, all the normalized reduced integral harmonic factors add up to the level of the zero order IHF, i.e. THD:

$$\overline{K}^{(n)}_{hu\_norm} \approx \overline{K}^{(0)}_{hu} = K_{hu} . \qquad (5)$$

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:

$$\overline{K}^{(1)}_{hu-aggr-sw} = \overline{K}^{(1)}_{hu\_norm} = N_{swph} \cdot \overline{K}^{(1)}_{hu} . \qquad (6)$$

As can be seen from (4) for n = 0, the switchings number inherently can not be taken into account for the THD itself.

So, ASIHF, related to (2), continue to be the only adequate generalized indices, reflecting these two the most important voltage generating aspects.

IV. Simulation Results and Discussion

The switchings (commutations) number in the MLVSI phase leg per the output voltage cycle N_{swph} dependences on the phase voltage amplitude modulation index m_{aY}, with step equal to 0.1, are presented in Fig. 3, a and b, respectively, for the two sub-ranges: $m_{aY} = 0.3...5$ and $m_{aY} = 5...10$.

Here the phase voltage amplitude modulation index is defined as follows:

$$m_{aY} = U / U_d = U^{*} , \qquad (7)$$

where U and U^{*} are the value and the relative value of the reference voltage space vector magnitude, equal to the reference phase voltage amplitude, U_d is the input dc voltage of the unit level (the base for all the voltages, marked with an asterisk *).

So, the delta voltage amplitude modulation index can be expressed as follows:

$$m_{a\Delta} = \sqrt{3} \cdot U^{*} = U^{*}_{\Delta m} = \sqrt{3} \cdot m_{aY} , \qquad (8)$$

and the amplitude modulation depth *M*, frequently used for the particular number *N* of the MLVSI levels, can be defined and related to the phase voltage amplitude modulation index by the equations:

$$M = U / U_{\max} = \frac{U}{(N-1) \cdot U_d} = \frac{U^{*}}{N-1} = \frac{m_{aY}}{N-1} , \qquad (9)$$

where $U^{*}_{\Delta m}$ is the amplitude relative value of the reference delta voltages, $U_{\max}$ is the maximum value of the voltage space vector magnitude provided by the *N*-level MLVSI.

Also in these two and the further provided figures the quarter-wave symmetric SVPWM [13]-[15] dependences are shown for the five lowest frequency modulation index m_f values: 12, 18, 24, 30 and 36, to be compared to the instantaneous SVC results. Here frequency modulation index is defined conventionally:

$$m_f = f_c / f , \qquad (10)$$

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

The zero to third orders ASIHF indices curves of their dependences on the phase voltage amplitude modulation index are presented in Fig. 4 and Fig. 5, respectively, for the same two phase voltage amplitude modulation index sub-ranges: $m_{aY} = 0.3...5$ and $m_{aY} = 5...10$.

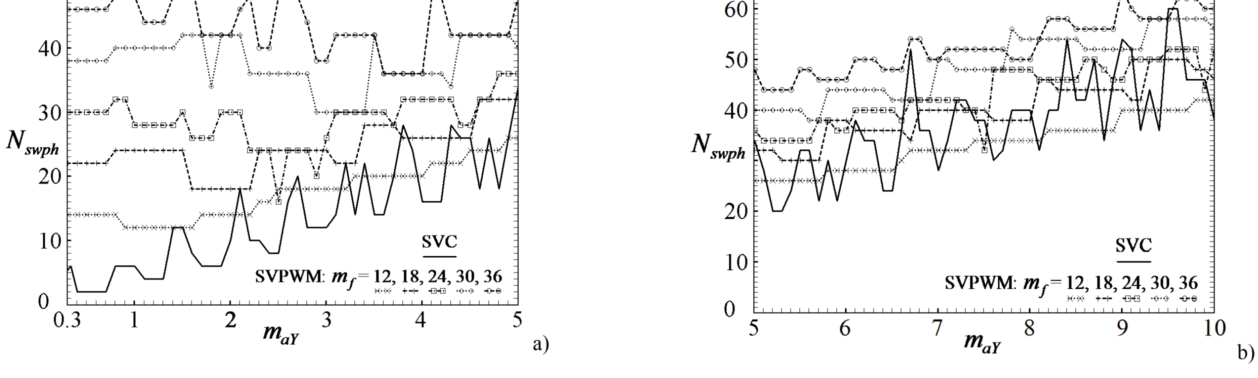

Fig. 3. Simulated results of the multilevel inverter phase leg per cycle switchings numbers: a) for the the range $m_{aY} = 0.3…5$; b) for the range $m_{aY} = 5…10$.

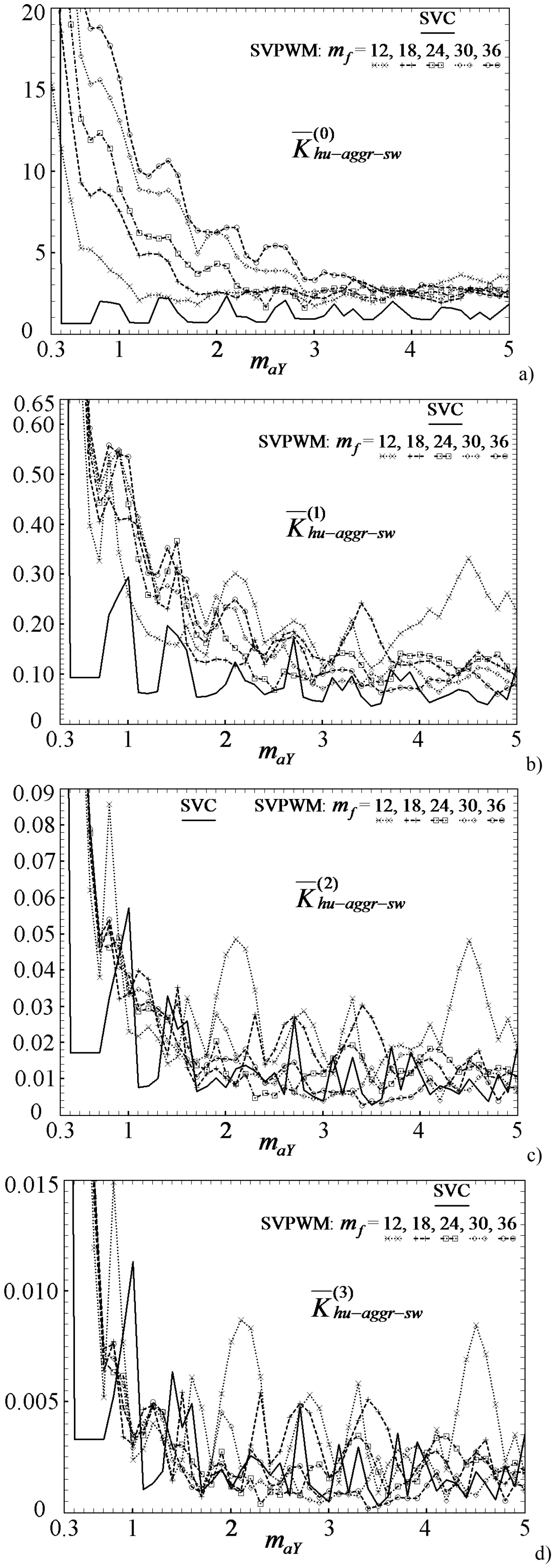

Fig. 4. Simulated zero-order (a) and first to three orders aggregate factors of switchings and integrated voltage harmonics (b, c and d) dependences on the phase amplitude modulation index m_{aY} for the instantaneous SVC and the quarter-wave symmetric SVPWM (under the five lowest values of the frequency modulation index) in the range m_{aY} = 0.3…5.

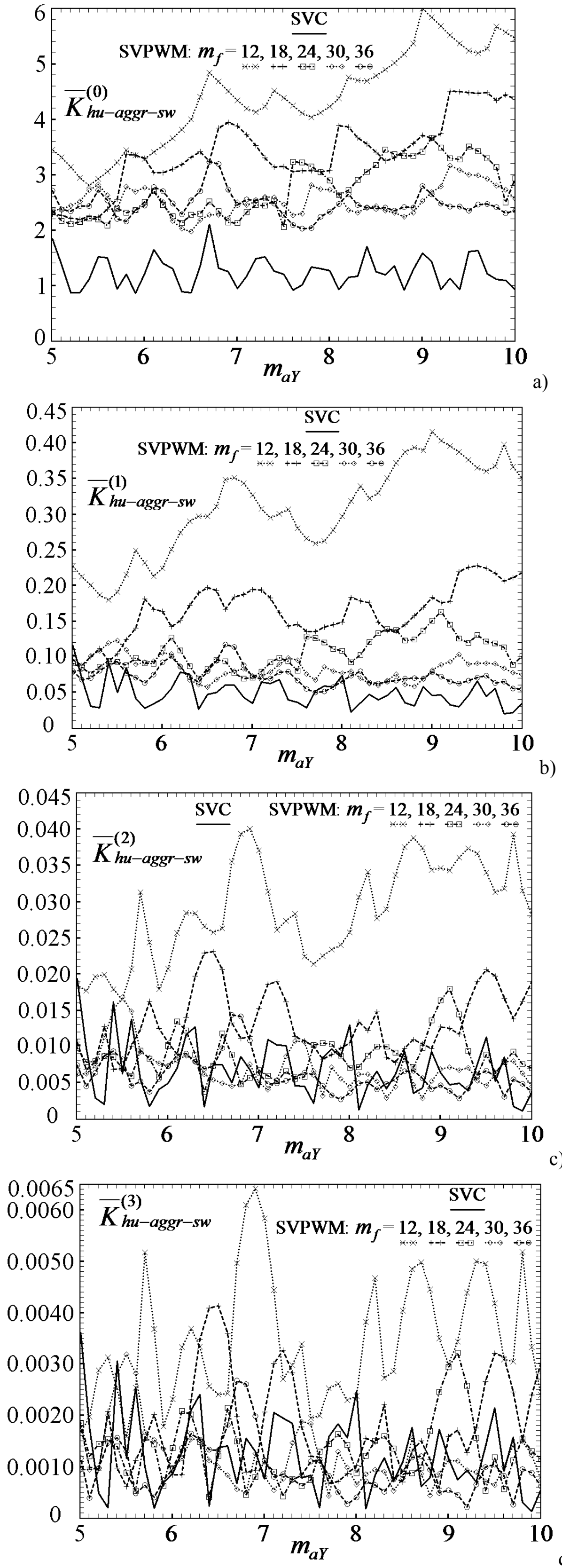

Fig. 5. Simulated zero-order (a) and first to three orders aggregate factors of switchings and integrated voltage harmonics (b, c and d) dependences on the phase amplitude modulation index m_{aY} for the instantaneous SVC and the quarter-wave symmetric SVPWM (under the five lowest values of the frequency modulation index) in the range m_{aY} = 5…10.

The sub-range $m_{aY} = U^* < 1/3$ is the zero-SV proximity zone, i.e. the dead band, for which all the MLVSI output instantaneous voltages are equal to zero.

The zero order ASIHF corresponds to the THD, and similar to the THD curves [18], the Fig. 4, a and Fig. 5, a demonstrate the SVC absolute superiority over the considered SVPWM modes in the zero order ASIHF values throughout the whole amplitude modulation index range, despite the relating to SVC per cycle switchings numbers are mostly higher than the corresponding SVPWM results for $m_f = 12$ in the second m_{aY} sub-range (see Fig. 3, b).

Equally sustainable competitive SVC advantage (with few exceptions) can be observed in the first-order ASIHF values.

But in values of the second-order and, especially, the third-order ASIHF the quarter-wave symmetric SVPWM successfully competes with SVC, at the frequency modulation index values, sequentially increasing with the growth of the amplitude modulation index value. This SVC drawback is caused by the high magnitude of fluctuations in second and third orders IHF values. It should be noted that, beginning from the first order ASIHF, values of these aggregate indices become the ambiguous functions of the amplitude modulation index (and also of the frequency modulation index for SVPWM).

Due to the proportion (3) of the ASIHF coefficients, the more the order ASIHF is, the less values of this ASIHF and its contribution to the corresponding output voltage or current THD are (just like in case of IHF values [21]).

But where the ac filters installation is envisaged, the respective order ASIHF indices are playing a growing role, and the above considered best SVPWM frequency modes should be applied.

Based on the joint approach and attributes of the before offered quarter-wave symmetric SVPWM and this novel SVC technique, the target might be to combine use of SVC and SVPWM with the output voltages quarter wave symmetry, applying one of the specified techniques depending on the range of amplitude modulation index values to obtaining voltage of the best quality of two alternatives with low dynamic losses in power semiconductor switches.

V. CONCLUSIONS

The n-order aggregate switchings and integrated voltage harmonics factors are used for the output voltage analysis of the three-phase multilevel inverter under the space vector control with the nearest vector selecting. These aggregate factors should be treated as the supplementary instrumentation for the comparison of the modulation algorithms for voltage generating which takes into account both the voltage quality and the price of its achieving. They must be further studied and developed to be correlated with the total power losses and the efficiency factor of the entire MLVSI circuit, including the output filter.

Based on the LabVIEW-simulated IHF results, curves of the ASIHF indices (from zero to third orders) dependences on the phase voltage amplitude modulation index (in its range from 0.3 to 10) are obtained for the SVC scheme and for the quarter-wave symmetric SVPWM (at the five low values of the frequency modulation index) for intercomparison.

Due to the SVC advantage in the zero and first orders aggregate indices, it can be strictly recommended for the loads which need no filter system. Otherwise, the choice of one of the two considered control techniques can be made via the above mentioned dependences curves by an industrial engineer who designs some system "MLVSI - filter - load circuit" for particular load circuit parameters values (they specify the most important orders numbers of IHF and ASIHF) and for selected amplitude modulation index ranges.

The supplementary researches are needed to solve the problem of MLVSI combined SVC and SVPWM control on the base of the general approach, operating with the integer and fractional parts of the reference delta voltages relative values. Such the control would preliminary assess the considered aggregate (voltage quality and dynamic losses) factors and apply the most suitable control technique.

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] 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.

[3] Stynski S. and Malinowski M. Space Vector Modulation in Three-Phase Three-Level Flying Capacitor Converter-Fed Adjustable Speed Drive. Chapter 10 in Advanced and Intelligent Control in Power Electronics and Drives. Springer, Switzerland, 2014, 410 p., 2014. Edited by T. Orlowska-Kowalska, F. Blaabjerg and J. Rodriguez, pp. 335-374.

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

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

[6] 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.

[7] Rodriguez J., Moran L., Silva C., Correa P. A high performance vector control of a 11-level inverter // IPEMC 2000, 3rd International Power Electronics and Motion Control Conference, Beijing, China, August 15-18, 2000, Proceedings, pp. 1116-1121.

[8] Rodriguez J., Correa P., Moran L. A vector control technique for medium voltage multilevel inverters // APEC 2001, 16th Annual IEEE Applied Power Electronics Conference and Exposition, Anaheim, CA, USA, March 4-8, 2001, Proceedings, pp. 173-178.

[9] 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.

[10] 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.

[11] 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.

[12] 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).

[13] 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.

[14] Lopatkin N.N., Zinoviev G.S. Voltage quality comparison of space vector PWM voltage source multilevel inverter under symmetric and nonsymmetric switching sequence variants: voltage harmonics integral factors // 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. 1-7.

[15] 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.

[16] 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).

[17] 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.

[18] 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.

[19] 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.

[20] 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.

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

[22] Bakhovtsev I.A., Zinoviev G.S. 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), Novosibirsk, 1987, 162 p., edited by G.V. Grabovetskiy, pp. 3-12 (in Russian).

[23] Zinoviev G.S. Direct Methods of Calculation of Power Indicators of Valve Converters. Novosibirsk: NSU, 1990. 220 p. (in Russian).

[24] Bakhovtsev I.A., Zinoviev G.S. Generalized analysis of output power of multiphase multilevel PWM voltage source inverters // Electricity, Iss. 4, 2016, pp. 26-33 (in Russian).

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