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Voltage THD and Integrated Voltage Harmonics Factors of Three-Phase Multilevel Voltage Source Inverter with Nearest Vector Selecting Space Vector Control

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***Abstract*—The paper deals with 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 LabVIEW model for the instantaneous SVC controller is designed. 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 amplitude modulation index and compared with the corresponding results of the quarter-wave symmetric space vector PWM (SVPWM).**

Keywords*—*multilevel inverter; voltage space vector control (SVC); barycentric coordinates; oblique-angled coordinates; quarter-wave symmetric space vector PWM of two delta voltages; THD; weighted THD; n-order integrated voltage harmonics factors (IHF); LabVIEW simulation

I. Introduction

The modulation technique is now the main instrument to provide high quality output AC voltage and current, high output capability, low losses in power switches, low cost of components or anything else parameters or acceptable combinations of the parameters values of the multilevel voltage source inverters (MLVSI) [1]-[3].

Increase in the MLVSI levels number makes it possible to avoid high switching frequency PWM while providing high output voltage quality. The space vector (SV) PWM (SVPWM) let us refuse to the growing number of the carriers and stricter requirements to their parameters values. But the further switching frequency reducing and the respective MLVSI efficiency increasing can be achieved only by replacing PWM with one of the so-called pseudo-modulation techniques [2].

In particular, the space vector control (SVC) with the nearest vector selecting becomes one of the most promising algorithms for industrial medium and high voltage converters with enough high number of levels. Originally, the SVC was described for cascaded multilevel inverter (CMLI) control [4]-[7], but obviously, it is equally attractive for use in different kinds of MLVSI circuits with high number of levels.

New nearest vector selecting technique has been developed in the context of the space vector algorithm of two delta voltages [8]-[11] which uses barycentric and affine (oblique-angled) coordinates on triangles of three nearest vectors to the reference one [12]. The offered 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. This approach to space vector control 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 [13].

II. Problem Definition

Analysis of voltage and current electrical signals harmonic compositions remains the main nonlinear circuits research technique. Despite the SVC is widely known since 2002, it is difficult to state that some absolutely general and comprehensive investigation of MLVSI output voltage quality under SVC has been implemented. The accessible publications, in particular pioneering papers [4]-[7], have considered the factor of voltage harmonics K_{hu} (HF), i.e. the classical voltage THD only.

The thorough research is needed to estimate also the integrated voltage harmonics factors (IHF) of the resulting MLVSI voltage as functions of the amplitude modulation index. These IHF indices 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 [14]-[19]. The IHF factors are closely related to the method of the differential equations algebraization (ADE) which allows finding asymptotically with the preset accuracy the closed analytical form expressions for the mathematical relations between the voltages and currents RMS values, using the coefficients of the integral-differential equation without solving it [14], [15].

Similar to the THD definitions, the n-order voltage IHF, $\overline{K}_{hu}^{(n)}$, is calculated as follows [14]-[16]:

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

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

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

where for estimated voltage u values $U_{(k)}$, $\overline{U}_{(1)}^{(n)}$, $\overline{U}_{(hh)}^{(n)}$ and $\overline{U}^{(n)}$ are the RMS value of the 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 conventional voltage THD (HF, K_{hu}) corresponds to $n = 0$.

The well-known weighted THD (WTHD) factor [20] completely corresponds to the first order IHF $\overline{K}_{hu}^{(1)}$, but this WTHD was used for the first time much later, approximately in 2000.

In accordance with (3), the n-order integrated voltage harmonics factors IHF can be also referred to as the n-order weighted THD [19]:

$$\overline{K}_{hu}^{(n)} = WTHD^{(n)}. \quad (5)$$

The IHF factors make it possible to evaluate beforehand the load circuit voltages and currents and their quality indices, such as the load (end user) current THD value. In this, these IHF indices relate not to some particular load circuit parameters and their some particular values, but to the impacting voltage itself (imposed to this load circuit).

The purpose of this paper is to propose the LabVIEW controller model for the instantaneous SVC [13], being the analog control technique close to the digital one with the tending to zero sampling period duration, and to provide curves of the THD and IHF indices dependences on the amplitude modulation index, as had been done for SVPWM (see [8], [9], [11], [21]-[23]).

Here, unlike [13], the phase voltage amplitude modulation index m_{aY} is used:

$$m_{aY} = U/U_d = U^*, \quad (6)$$

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 (base) level.

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

$$m_{a\Delta} = \sqrt{3} \cdot U^* = U_{\Delta m}^* = \sqrt{3} \cdot m_{aY}, \quad (7)$$

here $U_{\Delta m}^*$ is the amplitude relative value of the reference delta voltages.

The amplitude modulation depth M, 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:

$$M = U/U_{\max} = \frac{U}{(N-1) \cdot U_d} = \frac{U^*}{N-1} = \frac{m_{aY}}{N-1}, \quad (8)$$

where $U_{\max}$ is the maximum value of the voltage space vector magnitude provided by the N-level MLVSI.

III. Equivalent Circuits and LabVEW Model

The main needed IHF factors are being determined on the results of the ADE procedure, applied to differential equations that have been derived from some particular load circuits.

The simplified equivalent circuits of the MLVSI are shown in Fig. 1, where $u_{EXEag}(t)$ and $u_{EXEan}(t)$ are the phase "a" executed phase-to-ground ("g") and phase-to-neutral ("n") voltages, respectively; $\underline{z_a}$ is the phase "a" impedance, L_a and R_a are the prospective phase "a" load inductance and resistance, L_f and C_f are the elements of phase "a" MLVSI output LC filter; i_a is the phase "a" load current.

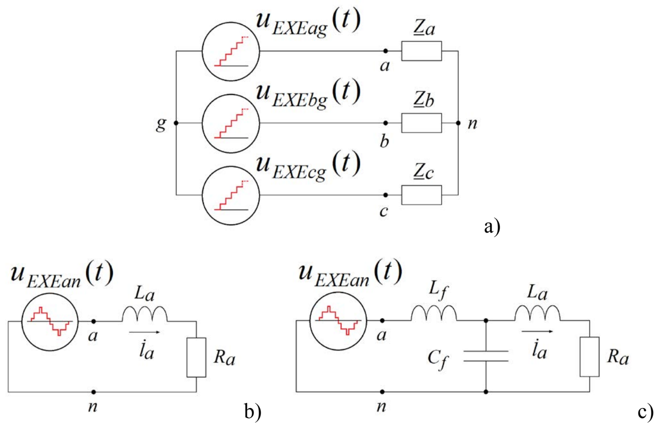


Fig. 1. MLVSI simplified equivalent circuits: three-phase circuit a), phase RL load circuit b), phase RL load circuit with MLVSI output filter c).

The simplest MLVSI load circuit (Fig. 1, b) produces the first order differential equation and reduced integral equation derived from it:

$$L_a \cdot \frac{di_a}{dt} + R_a \cdot i_a = u_{EXEan}\,,\; i_a + a_1 \cdot \overline{i}_a^{(1)} = b_1 \cdot \overline{u}_{EXEan}^{(1)}\,, \quad (9)$$

$$a_1 = R_a / L_a\,,\; b_1 = 1/L_a\,,$$

here and after the rest values designations completely correspond to description of (3). Let's here treat the $\overline{K}_{hu}^{(n)}$ as the n-order IHF of $u_{EXEan}(t)$.

After the ADE technique applying, the phase "a" load current i_a THD value can be defined as asymptotic quantity, being approximately calculated as the sum of the finite series with alternating members signs:

$$K_{hia} = I_{a(hh)} / I_{a(1)} \approx$$

$$\approx \sqrt{\left(a_1^2 + \omega^2\right) \cdot \sum_{n=1}^{N_f} \left\{ (-1)^{n-1} \cdot \left(\frac{a_1^{n-1}}{\omega^n} \cdot \overline{K}_{hu}^{(n)} \right)^2 \right\}}\,, \quad (10)$$

where N_f is the approximation level, related to the "filter hypothesis" [14], [15], namely $\overline{i}_{a(hh)}^{(n \ge N_f)} \equiv 0$. So, the first approximation $N_f = 1$ corresponds to

$$K_{hia} \approx \overline{K}_{hu}^{(1)} \cdot \sqrt{1 + \left(\frac{a_1}{\omega}\right)^2}\,. \quad (11)$$

The MLVSI phase load circuit with LC filter (Fig. 1, c) leads to the third order reduced integral equation and $N_f = 1$ approximation i_a THD result:

$$i_a + a_1 \cdot \overline{i}_a^{(1)} + a_2 \cdot \overline{i}_a^{(2)} + a_3 \cdot \overline{i}_a^{(3)} = b_3 \cdot \overline{u}_{EXEan}^{(3)}\,, \quad (12)$$

$$a_1 = \frac{R_a}{L_a}\,,\; a_2 = \frac{1}{C_f} \cdot \left(\frac{1}{L_f} + \frac{1}{L_a} \right),\; a_3 = \frac{R_a}{L_f \cdot C_f \cdot L_a}\,,$$

$$b_3 = \frac{1}{L_f \cdot C_f \cdot L_a}\,,$$

$$K_{hia} \approx \overline{K}_{hu}^{(3)} \cdot \sqrt{1 + \frac{a_1^2 - 2 \cdot a_2}{\omega^2} + \frac{a_2^2 - 2 \cdot a_1 \cdot a_3}{\omega^4} + \frac{a_3^2}{\omega^6}}\,. \quad (13)$$

Thus, the demanded IHF indices order numbers are strongly dependent on the whole MLVSI load circuit order and configuration, as well as on the approximation level N_f. In our case, the first three coefficients with $n = 1 \ldots 3$ are needed for the simplest circuit current i_a THD evaluation at the approximation level $N_f = 3$ according to (10), and the last of them is the main index for the load circuit with MLVSI output LC filter (and the only index at the level $N_f = 1$).

The LabVIEW controller and IHF-meter models are used here as proved to be useful and convenient [24], [25], [23].

The extended controller model, implementing the instantaneous SVC [13], is shown in Fig. 2. Here u^*_{REFab} and

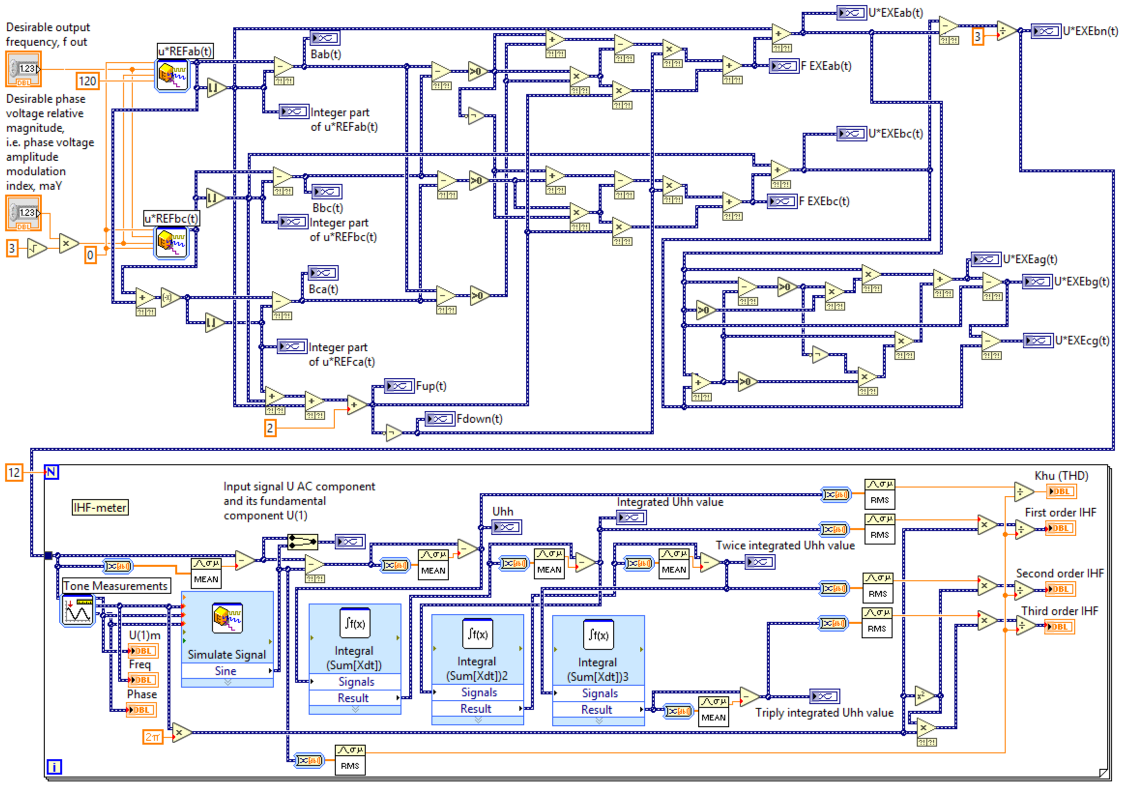


Fig. 2. LabVIEW "instantaneous SVC" controller model and IHF-meter for three-phase multilevel voltage source inverter with arbitrary level number N.

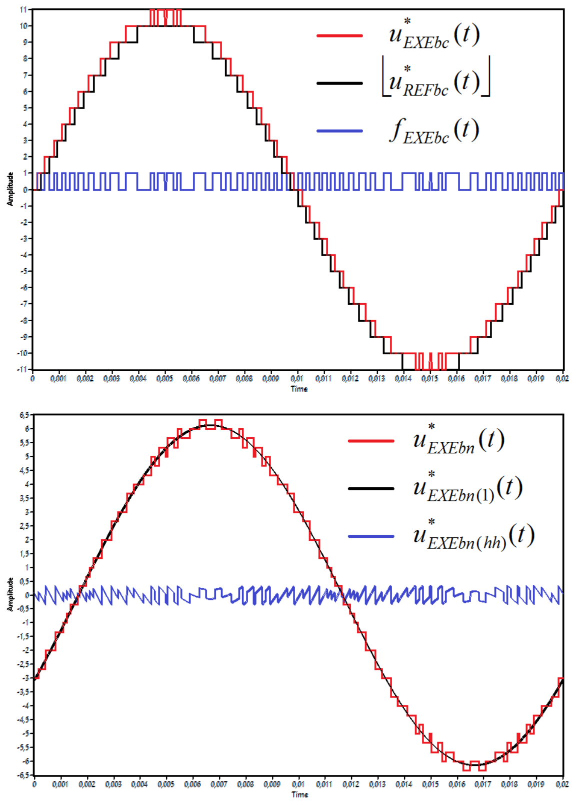
u^*_{REFbc} are the signals of the reference delta voltages, u^*_{EXEab} and u^*_{EXEbc} are the signals of the executed delta voltages, u^*_{EXEbn} is the signal of the executed phase-to-neutral voltage, and u^*_{EXEag}, u^*_{EXEbg} and u^*_{EXEcg} are the signals of the directly executed phase-to-ground voltages, respectively. Similar to (6), the voltages marked with an asterisk (*) are the relative values, in relation to the input DC voltage of the unity level U_d.

Except for some implementation details of the dynamic data logic processing, the considered LabVIEW SVC controller have replicated the respective Matlab/Simulink model [13].

IV. Simulation Results

The resulting instantaneous SVC delta and phase-to-neutral voltages waveforms have the quarter-wave symmetry and contain the same orders harmonics at any values of the amplitude modulation index, namely harmonics with numbers $n = 6 \cdot k \pm 1$, where *k* belongs to the natural numbers [13].

The waveforms of the executed delta voltage u^*_{EXEbc} and the components, which formed it [13], are shown in Fig. 3, a, and the waveforms of the executed phase-to-neutral voltage u^*_{EXEbn} and its fundamental and higher-order harmonics components are shown in Fig. 3, b for $m_{aY} = 6.12$.



a)
b)

Fig. 3. LabVIEW-simulated instantaneous SVC signals waveforms for $m_{aY} = 6.12$: a) executed delta voltage and forming it components, b) executed phase-to-neutral voltage and its fundamental and higher-order harmonics components.

The LabVIEW-simulated curves of the THD and first to third orders IHF indices dependences on the phase voltage amplitude modulation index, with step equal to 0.1, are presented in Fig. 4 and Fig. 5, respectively, for the two sub-ranges: $m_{aY} = 0.3...5$ and $m_{aY} = 5...10$. It should be noted that 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. Also in these two figures the quarter-wave symmetric SVPWM (see [10], [11], [22], [23]) dependences are shown for the five lowest values of the frequency modulation index: m_f = 12, 18, 24, 30 and 36, to be compared to the instantaneous SVC results. Here

$$m_f = f_c / f, \tag{14}$$

f_c and f are the clock and modulating frequencies respectively.

Fig. 4, a and Fig. 5, a demonstrate the SVC absolute superiority over the considered SVPWM modes in THD values throughout the whole amplitude modulation index range.

But in values of the various considered IHF indices the SVC approaches the best SVPWM results, that occur at m_f = 30 and 36, only when m_{aY} reaches value of about 4.3.

As for the $\overline{K}^{(2)}_{hu}$ and $\overline{K}^{(3)}_{hu}$ values in the second amplitude modulation index sub-range, the magnitude of fluctuations in their values is much higher in case of SVC compared to the above considered best SVPWM frequency modes.

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.

It seems reasonable that further study should consider the aggregate indices, which take into account both the voltage quality and the price of its achieving, namely the aggregate switchings and integrated voltage harmonics factors [26], [27], [22], [23].

V. Conclusions

The new 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. 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.

LabVIEW "instantaneous SVC" controller model for the linear mode of the three-phase arbitrary multilevel voltage source inverter is presented.

The role of the integrated voltage harmonics factors in MLVSI load current quality evaluation is demonstrated. The LabVIEW-simulated curves of the THD and first to third orders IHF indices dependences on the phase voltage amplitude modulation index in a wide enough range are obtained for the

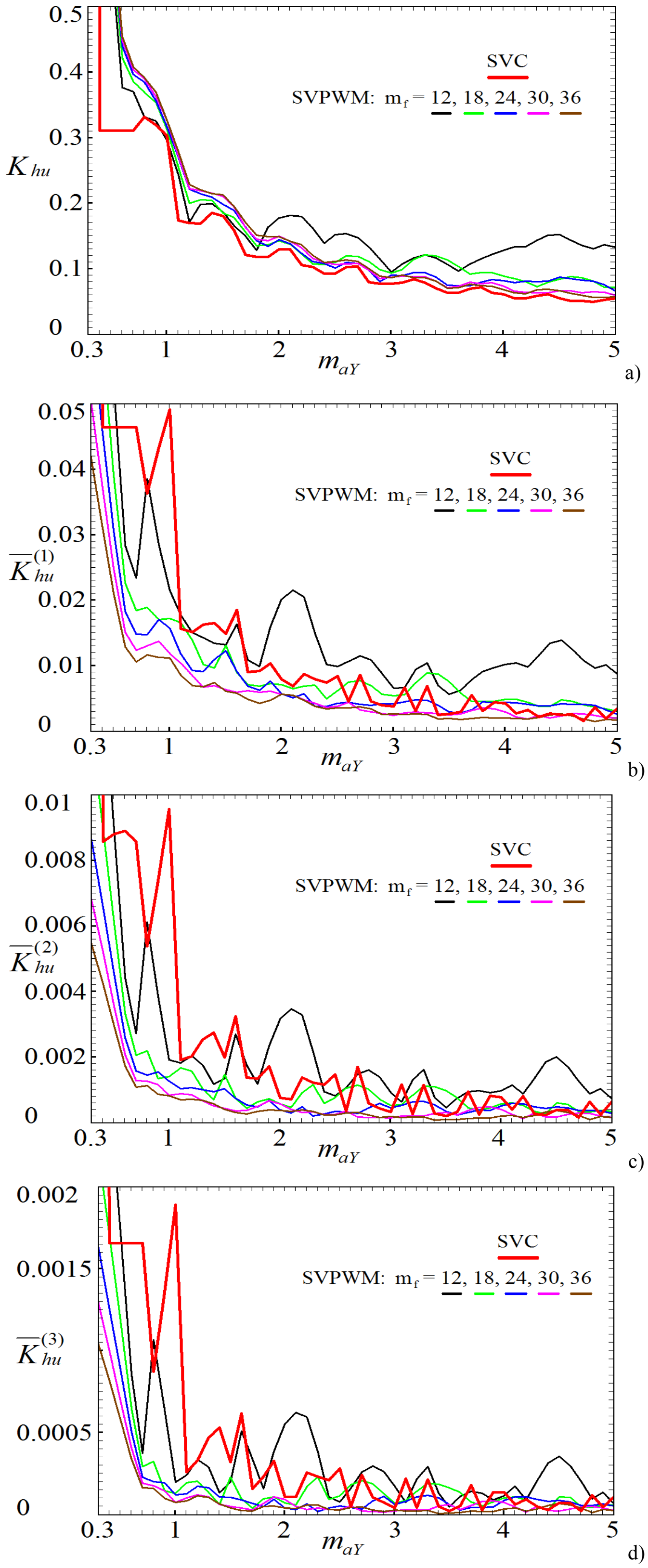


Fig. 4. LabVIEW-simulated THD (a) and first three orders IHF (b, c and d) dependences on the amplitude modulation index m_{aY} for the instantaneous SVC and the quarter-wave symmetric SVPWM (under the five lowest values of the frequency modulation index) in the range $m_{aY} = 0.3 \ldots 5$.

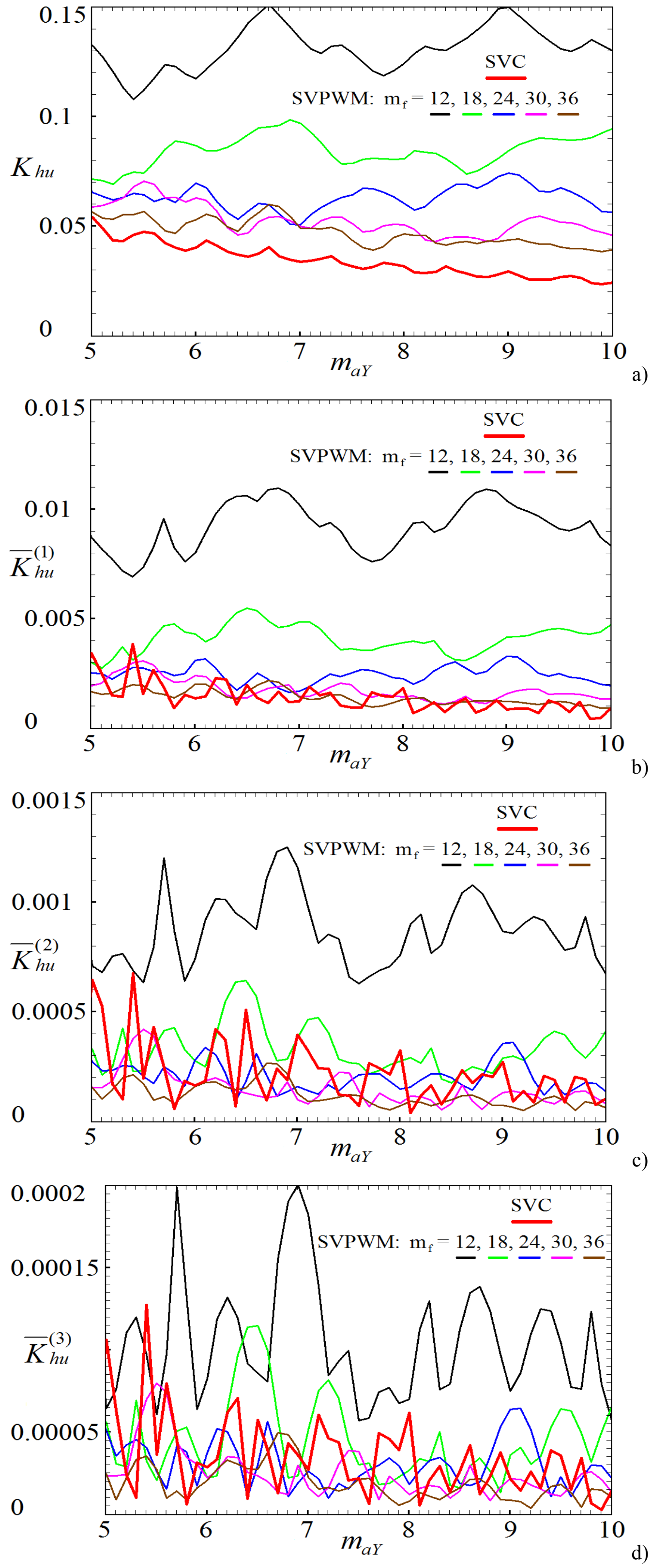


Fig. 5. LabVIEW-simulated THD (a) and first three orders IHF (b, c and d) dependences on the amplitude modulation index m_{aY} for the instantaneous SVC and the quarter-wave symmetric SVPWM (under the five lowest values of the frequency modulation index) in the range $m_{aY} = 5 \ldots 10$.

considered SVC scheme and compared to the relevant quarter-wave symmetric SVPWM dependences for the five lowest values of the frequency modulation index. The SVC advantage in the THD values and drawback in the IHF indices values at some amplitude modulation index sub-ranges are noted. The above mentioned dependences curves may be useful to industrial engineers who designs some system “MLVSI - filter - load circuit” for particular load circuit parameters values and uses the considered SVC and/or SVPWM control techniques.

The supplementary researches are needed to assess the impact of the reference voltages sample rate on the SVC output voltages quality and to compare the SVC and SVPWM aggregate switchings and integrated voltage harmonics factors dependences on the amplitude modulation index.

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