PSIM Model of Quarter-Wave Symmetric Space Vector PWM Modulator for Three-Phase Multilevel Voltage Source Inverter

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***Abstract*—The paper deals with PSIM-model implementation of the recently proposed quarter-wave symmetric (QWS) space vector PWM (QWS-SVPWM) technique, which provides the quarter-wave symmetry of the multilevel voltage source inverter (MLVSI) output voltages' waveforms, thereby reducing low order harmonics' content without increasing of switching frequency and related power losses in power switches. Basic details of the offered PSIM model of the QWS-SVPWM modulator are shown, explained and supported with some signals' waveforms. The delta voltages' relative reference signals and their sampling are described. The principle of generation of the delta voltages' output signals (the executed delta voltages signals) with use of the integer and fractional parts of the above mentioned samples is demonstrated. One of the ways of shaping of the directly executed output voltages' signals, namely phase-to-ground voltages' signals, is presented. Thanks to simplicity of QWS-SVPWM algorithm itself, all the model's solutions are implemented with use of very simple PSIM elements. The QWS-SVPWM modulator's model can be applied to control of a power circuit's PSIM model of a three-phase multilevel voltage source inverter of any circuit configuration and any levels' number under a regular diagram of voltage space vectors.**

Keywords—multilevel voltage source inverters, space vector PWM, quarter-wave symmetric space vector PWM, three-segment vectors switching sequence, integer and fractional parts of delta voltages relative values, PSIM model

I. Introduction

Thanks to progress in semiconductor power switches technology, multilevel voltage source inverters (MLVSI) show their readiness to industry implementation in medium and high level ranges both of voltage and of power [1-7].

Though the MLVSI control schemes seem to be well-established [8, 9], they have been subject to continuous improvements related to output AC power quality, output capability value, values of losses in power switches, cost of MLVSI components etc. [10, 11].

The recently proposed quarter-wave symmetric (QWS) space vector PWM (QWS-SVPWM) technique [12] provides the quarter-wave symmetry of the MLVSI output voltages' waveforms in addition to all the advantages of the space-vector PWM compared with carrier-based PWM schemes. The QWS waveform means reducing low order harmonics' content, whereas losses in power switches, related to switching frequency, remain on the low level.

QWS-SVPWM is based on the fast space-vector modulation algorithm [13] and uses integer and fractional parts of delta voltages relative values as the oblique-angled coordinates and the duty-cycles of the three modulating vectors, respectively. The unique modulating vectors' switching sequence was initially offered for the five-segment scheme [14], and then for the three-segment one, which has led to the above mentioned QWS-waveforms [12].

The whole developed PSIM model can be treated as composed of three main functional blocks (submodules), namely, a QWS-SVPWM modulator (controller), a switches' control interface and a power circuit.

The purpose of this paper is to describe basic details of the offered PSIM model of the quarter-wave symmetric space vector PWM modulator, which can be applied to control of a power circuit's PSIM model of a three-phase multilevel voltage source inverter of any circuit configuration and any levels' number under a regular diagram of voltage space vectors.

II. Reference Signals and Their Sampling

Here and after all the inverter phase voltages u_x and delta voltages u_{xy} (including the values with any additional subscript designations) have the relative values, which are marked with asterisks:

$$u_x^* = \frac{u_x}{U_d},\ u_{xy}^* = \frac{u_{xy}}{U_d}, \tag{1}$$

where U_d is the direct voltage of the unit (base) level.

The Mathcad model [12] defines the following continuous time-dependent functions of two relative delta voltages' reference signals, sampled and held in each clock cycle period:

$$u_{\text{sREFab}}^*(t) = m_{aD} \sin\left(\left(2\pi k(t) - \pi\right)/m_f + 2\pi/3\right),$$
$$u_{\text{sREFbc}}^*(t) = m_{aD} \sin\left(\left(2\pi k(t) - \pi\right)/m_f\right), \tag{2}$$

where m_{aD} is the delta voltage amplitude modulation index,

$$m_{aD} = \sqrt{3} \cdot m_{aY} = \sqrt{3} \cdot U/U_d, \tag{3}$$

m_{aY} is the phase voltage amplitude modulation index, U is the reference space vector (phase voltage vector) magnitude value;

m_f is the frequency modulation index,

$$m_f = f_c/f = T/T_c, \tag{4}$$

f_c, T_c and f, T are the clock frequency and period, and the modulating (output) frequency and period, respectively;

$k(t)$ is the continuous function for the clock cycle number and it runs the integer values from 1 to m_f within each MLVSI output voltage's period,

$$k(t)=\left\lfloor \left(t/T-\lfloor t/T \rfloor\right)\cdot m_f \right\rfloor + 1 = \left\lfloor \left(\frac{\omega t}{2\pi}-\left\lfloor\frac{\omega t}{2\pi}\right\rfloor\right)\cdot m_f \right\rfloor + 1, \quad (5)$$

where $\lfloor x \rfloor$ means the rounding down x to the closest integer number, taking into account the sign (the "floor" function), so $\lfloor x \rfloor$ is the integer part of x, and $\{x\} = x - \lfloor x \rfloor$ is the fractional part of x.

The value $\{t/T\} = t/T - \lfloor t/T \rfloor = \omega t/2\pi - \lfloor \omega t/2\pi \rfloor$ can be replaced by sawtooth wave, whose value grows from 0 to 1 within each output voltage's period.

However, PSIM provides simple and more convenient ways to obtain the results of (2) (u^*_{sREFab} and u^*_{sREFbc}), for example, by using Sample-and-Hold (Sampling/Hold) blocks, as it shown in Fig. 1. Signals in (2) and the instantaneous sinusoidal signals at inputs of these blocks here ($u^*_{\text{REFabSHIFT}}$ and $u^*_{\text{REFbcSHIFT}}$) have the specified initial phase angles in order to the sampled values correspond to the values of the initial reference sinusoidal functions (with the zero phase shift for the voltage $u^*_{\text{REFbc}}(t)$) at the midpoints of the clock cycles. The control signal of the Sample-and-Hold blocks is produced by Square-wave voltage source block and has frequency of $f \cdot m_f$ Hz, the duty cycle 0.5 of the high-potential interval, and zero phase delay.

Fig. 1 also shows the separation of the sampled relative delta voltages' reference signals into their integer and fractional parts, here

$$u^*_{\text{sintREFxy}} = \left\lfloor u^*_{\text{sREFxy}} \right\rfloor,$$

$$u^*_{\text{sfractREFxy}} = \left\{ u^*_{\text{sREFxy}} \right\} = u^*_{\text{sREFxy}} - \left\lfloor u^*_{\text{sREFxy}} \right\rfloor.$$

To eliminate the particularity of the Round-off function blocks in their dealing with negative quantities the operations of addition and subtraction of some constant, enough for MLVSI levels' number, are added.

The waveforms of signals $u^*_{\text{REFbcSHIFT}}$, u^*_{sREFbc}, $u^*_{\text{sintREFbc}}$ and $u^*_{\text{sfractREFbc}}$ are shown in Fig. 2 for $m_f = 18$, $m_{aY} = 3.2$.

III. Generation of Executed Voltages' Signals

The executed voltages' signals here mean the signals, whose waveforms should be repeated in the power circuit voltages' signals, including the output voltages' signals.

In accordance with the main principle of the two delta voltages shaping in QWS-SVPWM algorithm

$$u^*_{\text{EXExy}}(t) = u^*_{\text{s int REFxy}}(t) + f_{\text{sEXExy}}(t), \quad (6)$$

where $f_{\text{sEXExy}}(t)$ is pulse function, which can possess only the values 0 and 1, and both quantity and positions of the high-potential pulses depend on a sector's number, a type of a modulating vectors' triangle and values of $u^*_{\text{sfractREFab}}$ and $u^*_{\text{sfractREFbc}}$ for each clock cycle number [12].

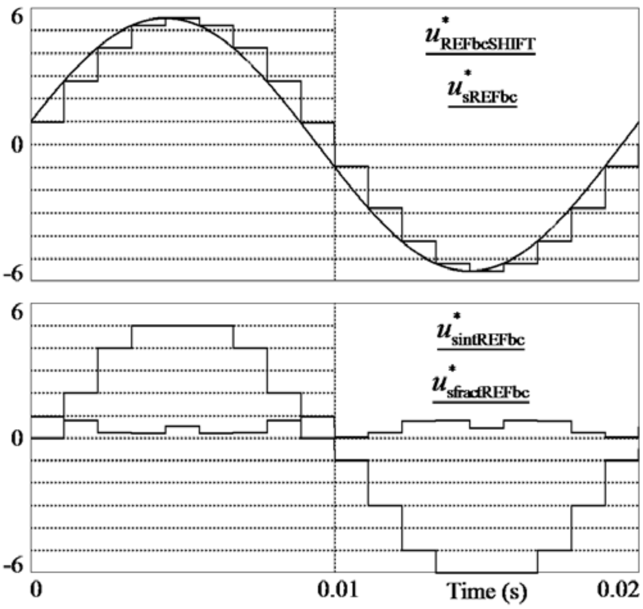

Fig. 2. Delta voltage's sinusoidal reference signal, sampled signal and its integer and fractional parts.

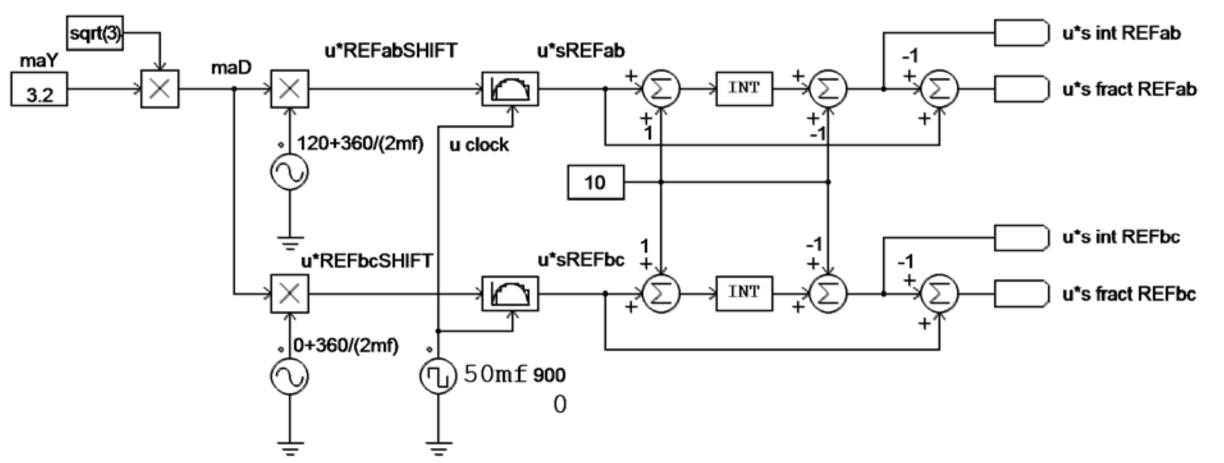

Fig. 1. Subcircuit for generation and sampling of two delta voltages' reference signals.

The clock-cycle mean value of this function is equal to the fractional part of the value of the related instantaneous reference delta voltage:

$$f_{\text{sEXExy\_mean\_}k} = u^*_{\text{sfractREFxy}}\,. \tag{7}$$

The full subcircuit for shaping of executed output delta voltage u^*_{EXEab} is presented in Fig. 3.

Here the square-wave voltage sources Fs1…Fs6 at the left side are the sectors' indicators: the only source of current active sector has high level signal's value. The sources Fs1…Fs6 have the frequencies' value equal to the output voltage frequency, the duty cycles' value of the high-potential interval equal to 1/6, the DC offsets' value equal to zero and the phase delays' values from 0 to 300 electrical degrees, with 60 electrical degrees shift of each subsequent signal relative to the previous one.

The signals Fsup and Fsdown are the indicators of the kinds of the current active modulating triangle, the up-pointing and down-pointing, respectively. Here the following up-pointing triangle's indicator is used:

$$\text{Fsup} = \frac{\text{sgn}\left(1 - u^*_{\text{sfractREFab}} - u^*_{\text{sfractREFbc}}\right) \ + \ 1}{2}, \tag{8}$$

where $\text{sgn}(x)$ is the standard signum function, implemented by PSIM Sign function block.

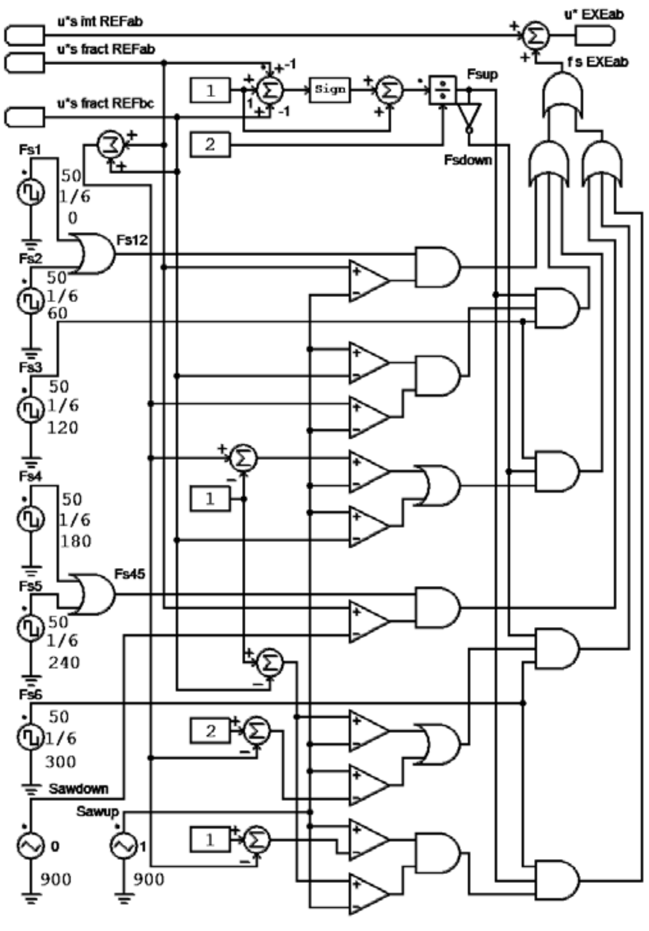

Fig. 3. Subcircuit for generation of one of two executed output delta voltages.

The Fsdown signal is the logical inversion of the Fsup signal.

The signals Sawup and Sawdown are the signals of the Triangular-wave voltage source blocks. They have the frequencies' value of $f \cdot m_f$ Hz, the peak-to-peak voltage amplitude value 1 V and the DC offsets' value equal to zero. Duty cycles of the rising slope intervals of the Sawup and Sawdown signals are 1 and 0, respectively, thus the Sawup signal is rising and the Sawdown signal is falling. These signals serve here as carrier signals related to time intervals within the clock cycles.

The second executed output delta voltage, u^*_{EXEbc} , is being formed in a similar vein, with use of the same indicator signals Fs1…Fs6, Fsup and Fsdown, the carrier signals Sawup and Sawdown, and information signals $u^*_{\text{sfractREFab}}$, $u^*_{\text{sfractREFbc}}$ and $u^*_{\text{sintREFbc}}$ [12, 14].

The phase-to-neutral executed output voltages can be calculated in accordance with the well known matrix equation:

$$\begin{bmatrix} u^*_{\text{EXEan}} \\ u^*_{\text{EXEbn}} \\ u^*_{\text{EXEcn}} \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix} \cdot \begin{bmatrix} u^*_{\text{EXEab}} \\ u^*_{\text{EXEbc}} \end{bmatrix}. \tag{9}$$

One of the ways to generate the directly executed phase-to-ground voltages' signals is shown in Fig. 4. As can be seen, these signals are being obtained as follows:

$$\begin{bmatrix} u^*_{\text{EXEag}}(t) \\ u^*_{\text{EXEbg}}(t) \\ u^*_{\text{EXEcg}}(t) \end{bmatrix} = \begin{bmatrix} k(t) \\ k(t) - u^*_{\text{EXEab}}(t) \\ k(t) - u^*_{\text{EXEab}}(t) - u^*_{\text{EXEbc}}(t) \end{bmatrix}, \tag{10}$$

$$k(t) = \max\left(0, u^*_{\text{EXEab}}(t), u^*_{\text{EXEab}}(t) + u^*_{\text{EXEbc}}(t)\right). \tag{11}$$

The waveforms of signals $u^*_{\text{sintREFab}}$, f_{sEXEab} , u^*_{EXEab} , u^*_{EXEan} and u^*_{EXEag} are shown in Fig. 5 again for $m_f = 18$, $m_{aY} = 3.2$.

The spectra of the generated signals of the executed output delta and phase-to-neutral voltages contain only harmonics (high or low level) of the orders $n = 6 \cdot k \pm 1$, where k runs (possess) values of the natural numbers [12].

The developed and presented PSIM-model of the QWS-SVPWM modulator has been used to control of a power circuit's PSIM model of a three-phase seven-level H-bridge cascaded voltage source inverter at low values of frequency modulation index [15].

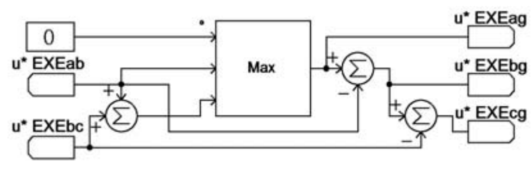

Fig. 4. Simple way to shape directly executed phase-to-ground voltages.

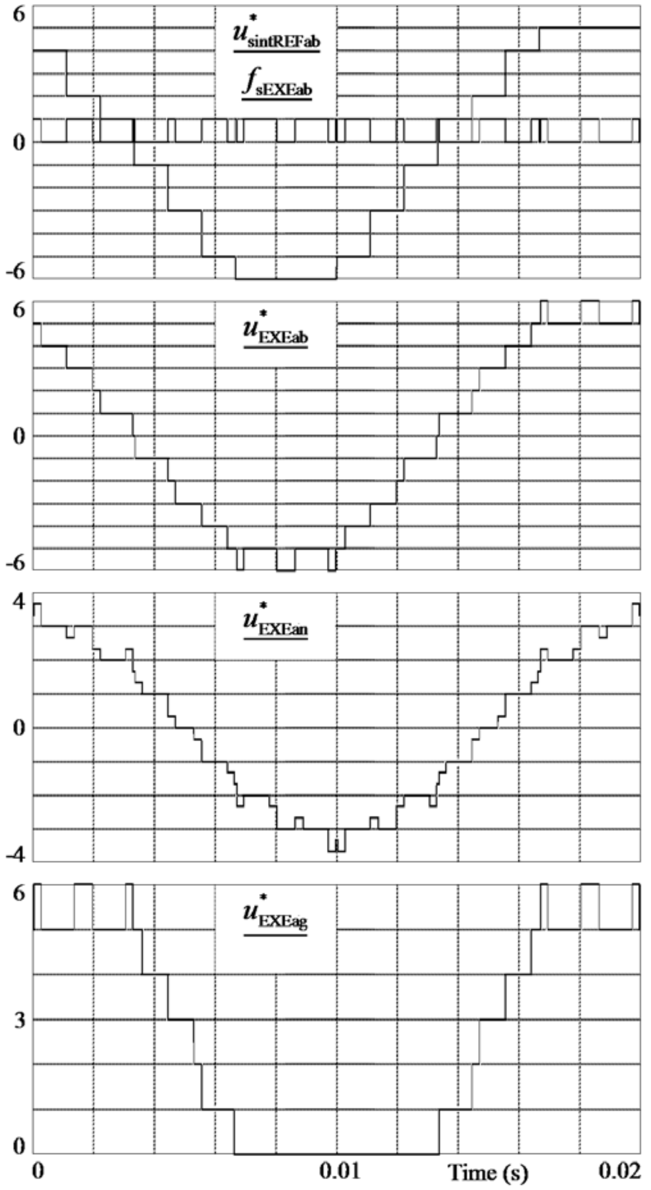

Fig. 5. Integer part of delta voltage's sampled reference signal and pulse function of executed delta voltage's signal; full signal of executed delta voltage; signal of executed phase-to-neutral voltage; signal of directly executed phase-to-ground voltage.

IV. Conclusions

The basic details of the PSIM model of the quarter-wave symmetric space vector PWM modulator, which can be applied to control of a three-phase multilevel voltage source inverter of any circuit configuration and any levels' number under a regular diagram of voltage space vectors, are presented. Compared to conventional techniques, QWS-SVPWM provides the output voltage with less higher-harmonics content at the same commutation frequency of power switches, or the less value of the commutation frequency at the same output voltage's quality.

The PSIM model of the QWS-SVPWM modulator makes it possible to investigate reactions to applying this technique to any power circuit's PSIM model of a multilevel voltage source inverter with any kind of a generalized load (including filter) and any number of inverter's levels. Namely, the simulated output voltages' and currents' quality (the harmonic content, namely voltages' and currents' THD and weighted THD) can be assessed. Such the simulated data would allow for engineering design of multilevel inverter based AC power supply systems with specified power quality.

Thanks to simplicity of the quarter-wave symmetric space vector PWM algorithm itself, all the model's solutions are implemented with use of very simple PSIM elements. This indirectly proves that this effective technique will have simple industrial implementation as well.

The offered PSIM model of the quarter-wave symmetric space vector PWM modulator has been successfully used in several simulations of the multilevel voltage source inverters.

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