PWM methods providing phase voltage symmetry of dual-inverter fed drives: Systems modeling and simulation

Abstract. Algorithms of space-vector-based synchronized pulsewidth modulation (PWM) have been applied for control of dual-inverter fed open-end winding induction motor drives supplied by two isolated dc-sources with non-equal voltages. Results of modeling and simulation of these systems proved the fact, that techniques of synchronized PWM provide continuous phase voltage symmetry (quarter-wave symmetry, or half-wave symmetry) for any ratios (integral or fractional) between the switching and fundamental frequencies of dual-inverter systems on the base of either standard inverters or neutral-point-clamped inverters, and also for any ratios between voltages of two dc-sources of the system.

Introduction

Cascaded (dual) converters which utilize two three-phase inverters are now perspective topologies for the medium-power and high-power systems, allowing multilevel output voltage in systems [1]-[6]. The structure of adjustable speed drives based on cascaded inverters is constructed by splitting the neutral connection of the induction motor and connecting both ends of each phase coil to inverters (Fig. 1).

It is known that for high-power/high-current drives (or for ultrahigh speed ac drives) it is necessary to provide elimination of undesirable sub-harmonics of voltage and current [7]-[9]. In order to avoid asynchronism of standard schemes of space-vector modulation, a novel method of synchronized PWM has been proposed, developed and disseminated for control of some topologies of power electronic converters, ac electric drives, and renewable energy systems [10]-[15].

In this paper, algorithms of space-vector-based synchronized PWM have been applied for control of asymmetrical dual-inverter fed open-end winding drive converters supplied by two isolated dc-sources with non-equal voltages. It had been analyzed two topologies of the system, based on either two standard inverters, or on two neutral-point-clamped inverters, controlled by specialized schemes of synchronized PWM, providing phase voltage symmetry for any operation conditions of the system.

Topology of asymmetrical dual-inverter fed motor drive

Fig. 1 presents basic structure of a dual-inverter fed open-end winding induction motor drive, where the INVERTER-1 and INVERTER-2 are standard three-phase voltage source inverters. Two isolated dc-sources with different (asymmetrical) voltages (Vdc and Vdc/2) are used in this case, and this ratio of dc-voltages allows providing of four-level waveforms of the phase voltage in the system [6].

Fig. 2 shows switching state vectors of two inverters, which provide avoidance of overcharging of the dc-link capacitors of the INVERTER-2 operating with lower dc-voltage [6]. The conventional definition for the switching state sequences (voltage vectors) for the switches of the phases of abc of each individual inverter is used here [10]. In particular, for the INVERTER-1: 1 - 100; 2 - 110; 3 - 010; 4 - 011; 5 - 001; 6 - 101, 0 - 000, 7 - 111 (1 - switch-on state, 0 - switch-off state); and the same definition are used for the INVERTER-2: 1' - 100'; 2' - 110'; 3' - 010'; 4' - 011'; 5' - 001'; 6' - 101', 0' - 000'; 7' - 111', where 1' - switch-on state of switches, and 0' - switch-off state.

Fig. 1. Asymmetrical dual-inverter fed drive with two dc-sources

Fig. 2. Voltage space-vector combinations, providing avoidance of overcharging of the dc-source capacitors with lower voltage

Fig. 3-4. Switching state sequences of two three-phase inverters at the switching frequency of the inverter 0°-90°

Features of the method of synchronized space-vector modulation

Algorithms of synchronized space-vector-based PWM allow providing continuously symmetry of phase voltage waveforms of drive converters, and can be used for control of each inverter in a dual-inverter system.

Figs. 3 - 4 present switching state sequences of three-phase inverter inside the interval 0°-90°. They illustrate two basic versions of space-vector PWM (Fig. 3 – continuous PWM (CPWM), and Fig. 4 – discontinuous PWM with the 30°-non-switching intervals (DPWM)) [10].

The upper traces in Figs. 3 – 4 are switching state sequences (in accordance with conventional designation [10]), then – the corresponding pole voltages of inverter. The lower traces in Figs. 3 - 4 show quarter-wave of the line-to-line output voltage of the inverter. Signals \( \gamma_k \) represent total switch-on durations during switching cycles \( \tau \), signals \( \gamma_k \) are generated in the centers of the corresponding \( \beta \). Widths of notches \( \lambda_k \) represent duration of zero states.
in accordance with
for CPWM,
between
$-1.11$ $\beta$ = $0.5 - 0.87 \tan((i - j - 0.25) \tau) \right] K_{ov2}
(5)
\beta_j = \beta_i \cos((j - 1 - K_s) \tau K_{ov1})
(4)
\gamma_j = \beta_{i-j+1} [0.5 - 0.87 \tan((i - j - 0.25) \tau)] K_{ov1}
(6)
\beta_i = \beta_i^* = \beta_i \cos((i - 1.25) \tau K_{ov1} \right] K_s
(7)
\gamma_i = \beta_i^* [0.5 - 0.87 \tan((i - 2.25) \tau) + \frac{(\beta_{i+1} + \beta_i + \lambda_{i-1})}{2}] K_s \right] K_{ov2}
(8)
\lambda_j = \tau - (\beta_j + \beta_{j+1}) / 2
(9)
\lambda_i = \lambda_i^* = (\tau - \beta_i^*) K_{ov1} K_s

where: $\beta_1 = 1.1 \tan (m F \max - \text{modulation index})$ if
$m < 0.907$, and $\beta_1 = \tau$ if $m > 0.907$
$K_{ov1} = 1$ until $F_{rst} = 0.907 F_{m}$, and $K_{ov1} = 1 - (F_{rst} - F_{ov1}) / (F_{ov1} - F_{rst})$ in
the zone between $F_{ov1}$ and $F_{ov2} = 0.952 F_{m}$; $K_{ov2} = 1$ until $F_{ov2}$, and $K_{ov2} = 1 - (F_{rst} - F_{ov2}) / (F_{ov2} - F_{rst})$
between $F_{ov2}$ and $F_{m}$; $K_0 = 0.25$ for DPWM, and $K_0 = 0$ for CPWM.

Algorithms of synchronized PWM for control of asymmetrical dual-inverter system

Control of each inverter of dual-inverter system on the
base of algorithms of synchronized PWM and in
accordance with the switching scheme, presented in Fig. 2,
allows providing continuous symmetry of phase voltage
waveforms during the whole control range of open-end
winding motor drive. Output voltages of two inverters have
opposite polarity in this case, with an additional phase shift
between voltage waveforms, which is equal to one half of
the switching interval (sub-cycle) $\tau$ (is equal to 0.5 $\tau$) [1].
The phase voltage $V_{as}$ of the system on the basis of
dual inverters (Fig. 1) is calculated in accordance with (10)-
(11) [6]:
(10)  
$V_0 = 1/3 (V_{a0} + V_{b0} + V_{c0} - V_{a2} - V_{b2} - V_{c2})$
(11)  
$V_{as} = V_{a0} - V_{b2}$
where $V_{a0}$, $V_{b0}$, $V_{c0}$, $V_{a2}$, $V_{b2}$, and $V_{c2}$ are the corres-
ponding pole voltages of each inverter, $V_0$ is zero sequence
(triplen harmonic components) voltage in the system.

For $j=2,...,i-1$:

\begin{align*}
\beta_j &= \beta_i \cos((j - 1 - K_s) \tau K_{ov1}) \\
\gamma_j &= \beta_{i-j+1} [0.5 - 0.87 \tan((i - j - 0.25) \tau)] K_{ov2} \\
\beta_i &= \beta_i^* = \beta_i \cos((i - 1.25) \tau K_{ov1} \right] K_s \\
\gamma_i &= \beta_i^* [0.5 - 0.87 \tan((i - 2.25) \tau) + \frac{(\beta_{i+1} + \beta_i + \lambda_{i-1})}{2}] K_s \right] K_{ov2} \\
\lambda_j &= \tau - (\beta_j + \beta_{j+1}) / 2 \\
\lambda_i &= \lambda_i^* = (\tau - \beta_i^*) K_{ov1} K_s
\end{align*}

One of the basic ideas of the proposed PWM method is
in continuous synchronization of positions of all central $\beta_i$ -
signals in the centers of the 60°-clock-intervals (fixing of
positions of the $\beta_i$-signals in the centers), with further
symmetrical generation of other active $\beta$ - and $\gamma$ -signals,
with the corresponding notches, around the $\beta_i$ -
signals.

Also, special signals $\lambda_i^*$ ( $\lambda_i$ for CPWM, $\lambda_i$ for DPWM
in Figs. 3-4) with the neighboring $\beta_i^*$ ( $\beta_i$ for CPWM, $\beta_i$
for DPWM) are formed in the clock-points ($0^\circ,60^\circ,120^\circ$...) of
the output curve. They are reduced simultaneously until
close to zero value at the boundary frequencies $F_i$
, providing a continuous adjustment of voltage with smooth
pulses ratio changing. $F_i$ is calculated in a general form as
a function of duration of sub-cycles $\tau$ in accordance with
(1), and the neighboring $F_{i-1}$ - from (2). Index $i$ is equal
equal here to number of notches inside a half of the 60°-clock-
intervals and is determined from (3), where fraction is
rounded off to the nearest higher integer [10]:

\begin{align*}
F_i &= 1/[6(2i - K_s) \tau] \\
F_{i-1} &= 1/[6(2i - K_s) \tau] \\
i &= (1/6F + K_s) \tau / 2
\end{align*}

where $K_s=1$, $K_s=3$ for continuous synchronized PWM,
$K_s=1.5$, $K_s=3.5$ for discontinuous PWM.

Equations (4)-(9) present set of control functions for
determination of durations of all control signals of three-
phase inverters with synchronized PWM in absolute values
(seconds) for both undermodulation and overmodulation
control regimes of inverters for scalar $V/F$ control mode [8].
As an illustration of control of dual-inverter system with synchronized PWM and with non-equal voltages of dc-sources ($V_{dc}$ and $V_{dc}/2$), Figs. 5–8 present pole voltages $V_{a1o}$ and $V_{a2o}$, zero sequence voltage $V_0$, and phase voltage $V_{as}$ (with spectrum of the $V_{as}$ voltage) of dual-inverter system with continuous (Figs. 5-6) and discontinuous (Figs. 7-8) synchronized PWM, for scalar control mode. The fundamental and switching frequencies of each inverter (averaged switching frequency for discontinuous PWM) are equal to $F=39Hz$ and $F_s=1kHz$, modulation indices of two inverters are equal to $m_1=m_2=0.78$, and ratio between the switching and fundamental frequencies is equal to $1000Hz/39Hz = 25.6$. Spectra of the presented voltage waveforms do not contain even harmonics and sub-harmonics.

Fig. 6. Spectrum of the phase voltage $V_{as}$ of the system with continuous synchronized PWM ($F=39Hz, F_s=1kHz$)

Fig. 7. Pole voltages $V_{a1o}$, $V_{a2o}$, zero sequence voltage $V_0$, and phase voltage $V_{as}$ of dual-inverter fed system with discontinuous synchronized PWM ($F=39Hz, F_s=1kHz, m_1=m_2=0.78$)

Fig. 8. Spectrum of the phase voltage $V_{as}$ of the system with discontinuous synchronized PWM ($F=39Hz, F_s=1kHz$)

An increased effectiveness of operation of power conversion systems on the base of dual inverters for some control modes can be provided by the corresponding control of switching frequencies of two inverters [6],[12]. In particular, for the analyzed asymmetrical open-end winding configuration of drive system, where lower dc-link voltage is one half of higher dc-link voltage, it is possible to increase correspondingly the switching frequency of the inverter supplied by lower dc-voltage. Figs. 9-10 present the corresponding basic voltage waveforms and spectra of the phase voltage for the system with discontinuous synchronized PWM with different switching frequencies of two inverters ($F_{s1}=1kHz, F_{s2}=2kHz$).

Fig. 9. Pole voltages $V_{a1o}$, $V_{a2o}$, zero sequence voltage $V_0$, and phase voltage $V_{as}$ of dual-inverter fed system with discontinuous synchronized PWM ($F=39Hz, F_{s1}=1kHz, F_{s2}=2kHz, m_1=m_2=0.78$)

Fig. 10. Spectrum of the phase voltage $V_{as}$ of the system with discontinuous synchronized PWM ($F=39Hz, F_{s1}=1kHz, F_{s2}=2kHz$)

Fig. 11. Pole voltages $V_{a1o}$, $V_{a2o}$, zero sequence voltage $V_0$, and phase voltage $V_{as}$ of dual-inverter fed system with discontinuous synchronized PWM ($F=32Hz, V_{dc2}=0.7V_{dc1}, F_{s1}=1kHz, F_{s2}=1.43kHz, m_1=m_2=0.64$)

It is necessary to mention, that algorithms of synchronized modulation allow providing symmetry of phase voltage waveforms of dual-inverter system for any ratio between dc-voltages of two isolated dc-sources (and also for any switching frequencies of two inverters). As an illustration of this fact, Figs. 11-12 show basic voltage waveforms and spectra of the phase voltage for the system with two dc-voltages $V_{dc2}=0.7V_{dc1}$ with discontinuous synchronized PWM for scalar control mode. The fundamental frequency of inverters is equal to $F=32Hz$ (modulation indices of two inverters $m_1=m_2=0.64$ in this case), and switching frequencies of two inverters are equal correspondingly to $F_{s1}=1kHz$ and $F_{s2}=1.43kHz$. 

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In particular, spectra of the presented phase voltage waveforms (see Figs. 6, 8, 10, 12) do not contain even harmonics and sub-harmonics for any operating conditions of dual-inverter-based opened-end winding drive system. Method of synchronized space-vector modulation allows providing also high quality linear control of the fundamental voltage of dual-inverter system in the zone of overmodulation too [10], [12].

Fig. 12. Spectrum of the phase voltage $V_{a}$ of the system with discontinuous synchronized PWM ($F=32\text{Hz}$, $V_{dc2}=0.7V_{dc1}$, $F_{s1}=1\text{kHz}$, $F_{s2}=1.43\text{kHz}$)

Dual-inverter system on the base of neutral-point-clamped inverters

In order to increase effectiveness of operation of asymmetrical dual-inverter fed open-end winding motor drive, it is possible also to use dual neutral-point-clamped inverters as basic components of dual-inverter topology. In particular, specialized control scheme allows to provide elimination of zero sequence voltages in dual-inverter system on the base of neutral-clamped inverters [11], [13], [15]. Fig. 13 presents basic topology of a neutral-clamped inverter. Each of the three legs of the inverter consists of four power switches, four freewheeling diodes and two clamping diodes.

Fig. 14. Switching state vectors providing elimination of zero sequence voltage in inverter system

Fig. 15. Pole voltages $V_{a1o}$, $V_{a2o}$, zero sequence voltage $V_{o}$, and phase voltage $V_{as}$ of dual-neutral-clamped-inverter system with discontinuous PWM ($F=39\text{Hz}$, $F_{s}=1\text{kHz}$, $m_{1}=m_{2}=0.78$)

Fig. 16. Spectrum of the phase voltage $V_{a}$ of system with neutral-clamped inverters with discontinuous PWM ($F=39\text{Hz}$, $F_{s}=1\text{kHz}$)

Fig. 17. Basic voltages of dual-inverter fed system with neutral-clamped inverters with "direct-direct" synchronized PWM ($F=39\text{Hz}$, $F_{s}=1\text{kHz}$, $m_{1}=m_{2}=0.78$)

Fig. 18. Spectrum of the phase voltage $V_{a}$ of system with neutral-clamped inverters with "direct-direct" PWM ($F=39\text{Hz}$, $F_{s}=1\text{kHz}$)

Figs. 15-18 present pole voltages $V_{a1o}$ and $V_{a2o}$, zero sequence voltage $V_{o}$, and phase voltage $V_{as}$ (with spectrum of the $V_{as}$ voltage) of asymmetrical ($V_{dc2}=0.5V_{dc1}$) dual-inverter system on the base of neutral-clamped inverters with discontinuous (DPWM [13], Figs. 15-16), and "direct-direct" (DDPWM [13], Figs. 17-18) schemes of synchronized PWM, for scalar $V/F=const$ control mode.

The fundamental and switching frequencies of each inverter are equal correspondingly to $F=39\text{Hz}$ and $F_{s}=1\text{kHz}$, modulation indices of two neutral-clamped inverters are equal to $m_{1}=m_{2}=0.78$, and ratio between the switching and
fundamental frequencies is equal to 1000Hz/39Hz=25.6 in this case. Spectra of the phase voltage of this topology of dual-inverter system with synchronized PWM do not contain undesirable even harmonics and sub-harmonics.

Spectral characteristics of the phase voltage

Fig. 19 presents the calculation results of Weighted Total Harmonic Distortion factor

\[
WTHD = \left( \frac{1}{V_{as}} \right) \sum_{k=2}^{m} \left( \frac{V_{ak}}{V_{as}} \right)^{0.5}
\]

for the phase voltage \( V_{as} \) as function of modulation index \( m = m_1 = m_2 \) of two inverters of asymmetrical drive \( (V_{dc2} = 0.5V_{dc1}) \) on the base of two two-level inverters (with algorithms of continuous (CPWM) and discontinuous (DPWM) synchronized PWM), and also on the base of two neutral-clamped inverters, controlled by algorithms of the "direct-direct" (DDPWM-NPC) and discontinuous (DPWM-NPC) schemes of synchronized modulation. Control mode of the system corresponds to scalar \( V/F \) control (linear modulation zone), and the average switching frequency of each inverter of dual-inverter system is equal to \( F_s = 1kHz \).

The presented calculation results show that dual-inverter systems on the base of neutral-clamped inverters with specialized algorithms of synchronized PWM have better spectral composition of the phase voltage (in comparison with the system on the base of standard inverters) in the zone of low and medium modulation indices of inverters. In the case of dual-inverter topology on the base of two-level inverters algorithms of discontinuous synchronized PWM allow better spectral composition of the phase voltage in the zone of higher fundamental frequencies.

Conclusion

Algorithms of space-vector-based synchronized PWM, disseminated for control of asymmetrical dual-inverter fed open-end winding motor drive on the base of either two standard inverters or two neutral-point-clamped inverters with specialized scheme of modulation, supplied by two isolated dc-sources \( (V_{dc2}=0.5V_{dc1}) \), allow continuous symmetry (quarter-wave symmetry, or half-wave symmetry) of multilevel phase voltage waveforms during the whole control range and for any operating conditions.

Results of modeling and simulation proved the fact, that algorithms of synchronized PWM provide symmetry of multilevel phase voltage of dual-inverter systems:

- for any ratio (integral or fractional) between the switching frequency and fundamental frequency of each inverter of open-end winding motor drive;
- for the case of non-equal switching frequencies of two inverters of dual-inverter system;
- for any ratio of voltage magnitudes of two dc-sources.

Spectra of the phase voltage of dual-inverter-based drives controlled by algorithms of synchronized pulsedwidth modulation do not contain even harmonics and sub-harmonics, which is especially important for the systems with an increased power rating.

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