УДК 621.314.572

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HYBRID VEHICLE DRIVE WITH SYNCHRONOUSLY MODULATED DUAL INVERTERS

Analysis of operation of propulsion electric drive system with asymmetrical six-phase induction motor, supplied by the battery and fuel cells, has been performed. Power conversion part of the drive includes two neutral-point-clamped inverters, controlled by algorithms of synchronised pulsewidth modulation (PWM), providing both continuous phase voltage synchronization and common-mode voltage cancellation in the system.

Выполнен анализ работы системы транспортного электропривода с шестифазным электродвигателем асимметричного типа, с автономным комбинированным электроснабжением от батареи и топливных элементов. Преобразовательная часть электропривода включает два инвертора напряжения со средней точкой в цепи источника питания, регулируемых на базе алгоритмов синхронной широтно-импульсной модуляции (ШИМ), обеспечивающих как непрерывную синхронизацию фазных напряжений, так и устранение напряжений нулевой последовательности в системе.

Introduction. Multiphase power conversion systems have been exciting an increasing interest during the last years due to some advantages compared with standard three-phase systems, especially for the systems with an increased power rating [1,2,10]. As an example of asymmetrical multiphase traction drive system with two DC voltage sources, Fig. 1, *a* presents topology of the electrical vehicle system on the base of the six-phase induction motor supplied by two inverters with two different DC links: 1) Battery DC link with the V_{dc1} voltage, and 2) Fuel Cell DC link with the V_{dc2} voltage [1]. The induction machine has in this case two sets of winding spatially shifted by 30 electrical degrees with isolated neutral points (Fig. 1, *b*) [1].

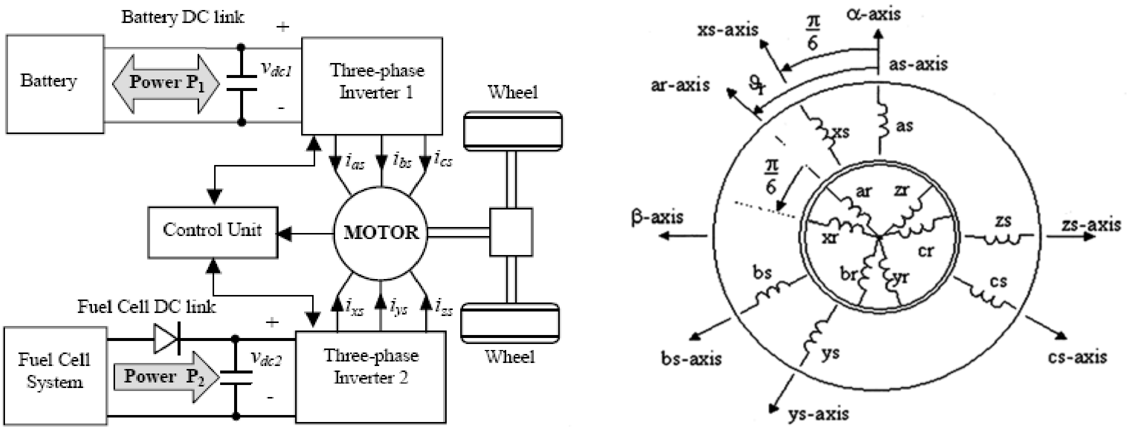
Typical configuration of six-phase (dual three-phase) drives is based on the two standard voltage source inverters [1,2]. At the same time the use of neutral-point-clamped inverters can provide some improvements in operation of asymmetrical dual three-phase drives. In particular, some specific control schemes and algorithms can provide full elimination of undesirable alternating common-mode voltages in the systems with dual neutral-point-clamped converters [6,9].

In order to provide synchronization of the voltage waveforms of inverters, novel techniques of synchronized pulsewidth modulation (PWM) have been recently proposed for three-level converters [4]. So, this paper is focused on analysis of operation of asymmetrical six-phase traction drive based on dual neutral-point-clamped inverters, controlled by novel PWM algorithms, providing both cancellation of common-mode voltages (both on the outputs of each inverter and in the load), and also phase voltages synchronization during the whole control range.

Three-Phase Neutral-Point-Clamped Inverter with Specialized Algorithms of PWM. Fig. 2, *a* presents basic topology of a three-level neutral-clamped inverter (of the first inverter with the phases *a*, *b*, *c*). Each of the three legs of the inverter consists of four power switches, four freewheeling diodes and two clamping diodes. Fig. 2, *b* shows the switching state vectors of the inverter. Generally, there are twenty-seven different switching states, which correspond to nineteen vectors shown by the big and small arrows in Fig. 2, *b* [8].

Recently, new algorithms of PWM have been proposed for three-level inverters, providing elimination of undesirable alternating common-mode voltages, which are the main reason for bearing currents and bearing failures in induction motor drives with PWM [6],[9]. It is leading to an increase of the reliability and the life period of the drive systems.

Twelve (six and six) switching state vectors are located on the periphery of the two presented hexagons, and six small vectors have the position in the middle of the corresponding big vectors. There is also a zero voltage vector. Generally, it can be represented by three different switching states. It is known, that using only seven of the vectors, $\boldsymbol{V}_1$ ¯ $\boldsymbol{V}_7$, marked in Fig. 2, *b* by the big arrows with the corresponding number of the vector, this can provide elimination of the common-mode voltage in a three-phase load [4,6,9].



a *b*

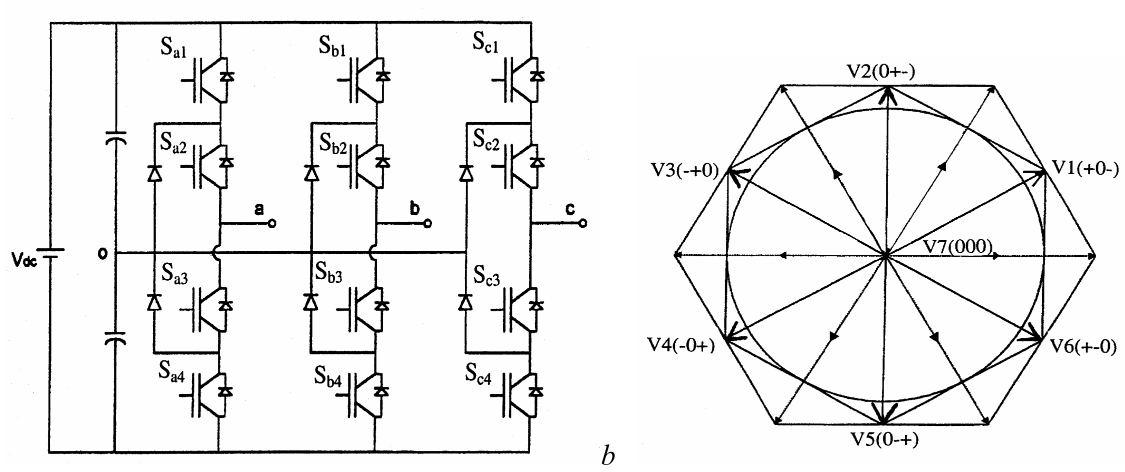
Fig. 1.

A ternary switching variable (+,0,-) is defined for the switches of each of the three phase as:

+ if $\boldsymbol{S_1}$, $\boldsymbol{S_2}$ are ***ON*** and $\boldsymbol{S_3}$, $\boldsymbol{S_4}$ are ***OFF***;
0 if $\boldsymbol{S_2}$, $\boldsymbol{S_3}$ are ***ON*** and $\boldsymbol{S_1}$, $\boldsymbol{S_4}$ are ***OFF***;
\- if $\boldsymbol{S_3}$, $\boldsymbol{S_4}$ are ***ON*** and $\boldsymbol{S_1}$, $\boldsymbol{S_2}$ are ***OFF***.

Switching state sequences can be written in this case for the corresponding vectors as:

$$V_1(+0-);\ V_2(0+-);\ V_3(-+0);\ V_4(-0+);\ V_5(0-+);\ V_6(+-0);\ V_7(000).$$



a *b*

Fig. 2.

Synchronous PWM Control of Dual Three-Phase System. In order to avoid asynchronism of standard space-vector modulation, a novel method of synchronized PWM can be used for control of each inverter in six-phase drive system [3].

Control of asymmetrical dual three-phase drives is based on the 30^0-phase-shift of the signals of two inverters with the phases ***a, b, c***, and ***x, y, z*** [1,2,10]. In accordance with the theory of vector space decomposition, the basic six-dimensional space (*as, bs, cs, xs, ys, zs*) of a dual-three phase induction machine with isolated neutral points can be transformed into two orthogonal two-dimensional subspaces (*sa, sb*) and (*m*1, *m*2) [10]. Voltage components V_{sa}, V_{sb}, V_{m1} and V_{m2} in these subspaces, and also the phase voltages V_{as} and V_{xs} and common mode voltage V_0, are calculated as [10]:

$$V_{sa}=0.333(V_a-0.5V_b-0.5V_c+0.866V_x-0.866V_y), \quad (1)$$

$$V_{sb}=0.333(0.866V_b-0.866V_c+0.5V_x+0.5V_y-V_z), \quad (2)$$

$$V_{m1}=0.333(V_a-0.5V_b-0.5V_c-0.866V_x+0.866V_y), \quad (3)$$

$$V_{m2}=0.333(-0.866V_b+0.866V_c+0.5V_x+0.5V_y-V_z), \quad (4)$$

$$V_{as}=V_{sa}+V_{m1}=V_a-0.333(V_a+V_b+V_c), \quad (5)$$

$$V_{xs}=V_{sb}+V_{m2}=V_x-0.333(V_x+V_y+V_z), \quad (6)$$

$$V_0=0.333(V_a+V_b+V_c+V_x+V_y+V_z), \quad (7)$$

where V_a, V_b, V_c, V_x, V_y, V_z – are the corresponding pole voltages of two three-level inverters (see Fig. 1, *a* and Fig. 2, *a*).

In this case, the V_{sa} and V_{sb} components, which produce useful rotating MMF *k*-th order voltage harmonics ($k=12m\pm1$, m=1,2,3,..), are the useful components. But the V_{m1} and V_{m2} components, which generate loss-producing harmonics ($k=6m\pm1$, m=1,3,5,..), are the undesirable voltage components [10].

Fig. 3 – Fig. 5 present basic voltage waveforms (phase voltages V_{as} and V_{xs} and its useful components V_{sa} and V_{sb}, common-mode and line voltages V_0 and V_{ab}, and spectra of the V_{as} and V_{sa} voltages) of dual three-phase vehicle drive with two DC sources with equal voltages ($V_{dc1}=V_{dc2}$) under standard scalar *V/F* control during a period of the fundamental frequency. Modulation indices of two inverters are equal in this case too ($m_1=m_2$).

In particular, Fig. 3 illustrates behaviour of six-phase drive system with continuous synchronized PWM [3,8]. Fig. 4 presents basic voltage waveforms and its spectra for the system with discontinuous synchronized PWM [4,8], and Fig. 5 shows basic voltage waveforms (with spectra of the V_{as} and V_{sa} voltages) for the system with the “direct-direct” scheme of PWM [4,6,7]. The switching and fundamental frequencies of each neutral-point-clamped inverter of the dual system are F_s=900 Hz and F=42 Hz ($m_1=m_2=0.84$).

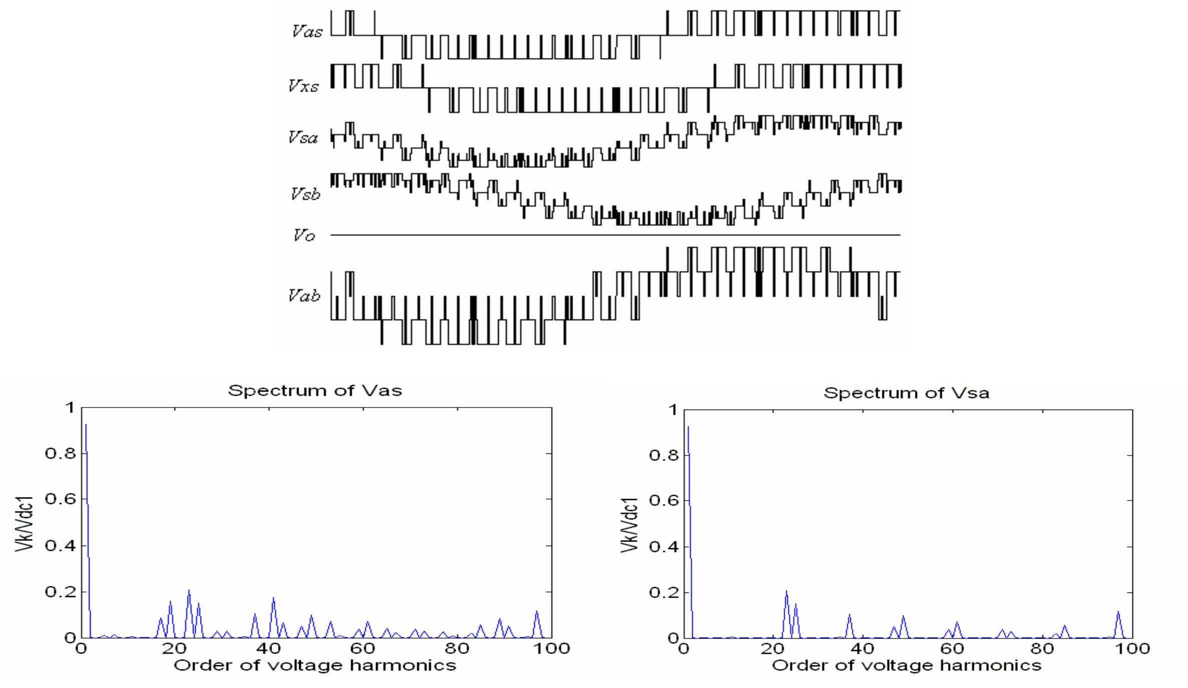


Fig. 3.

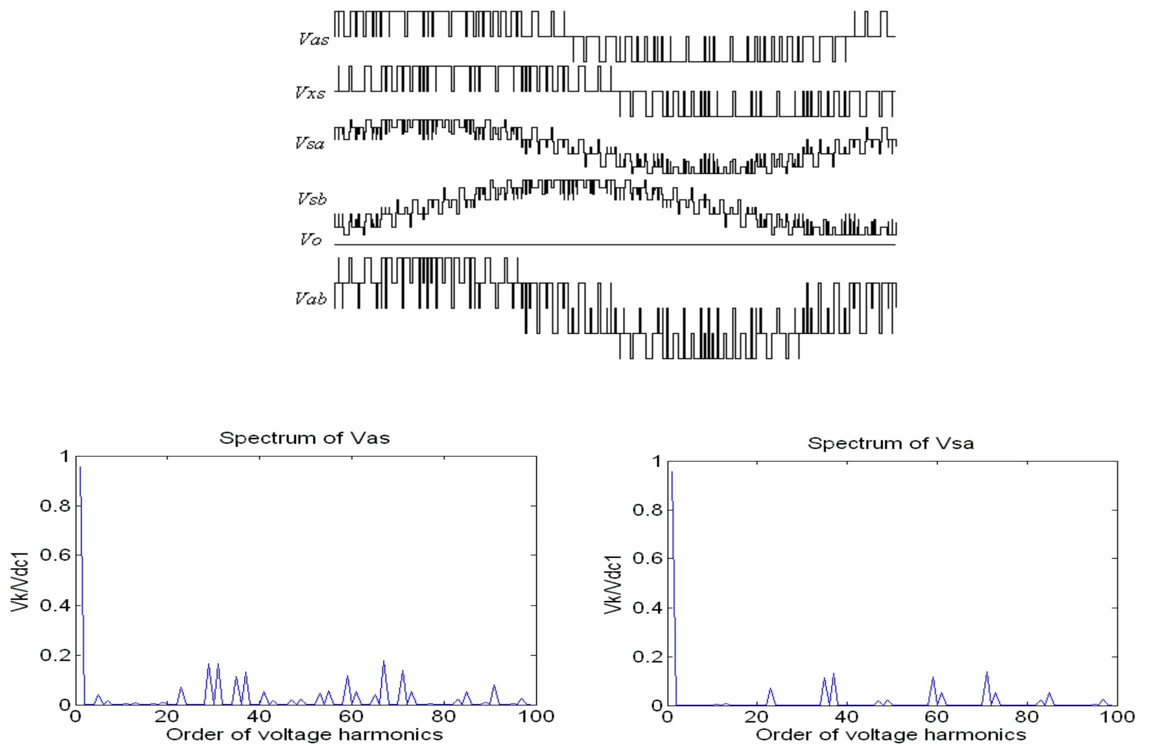


Fig. 4.

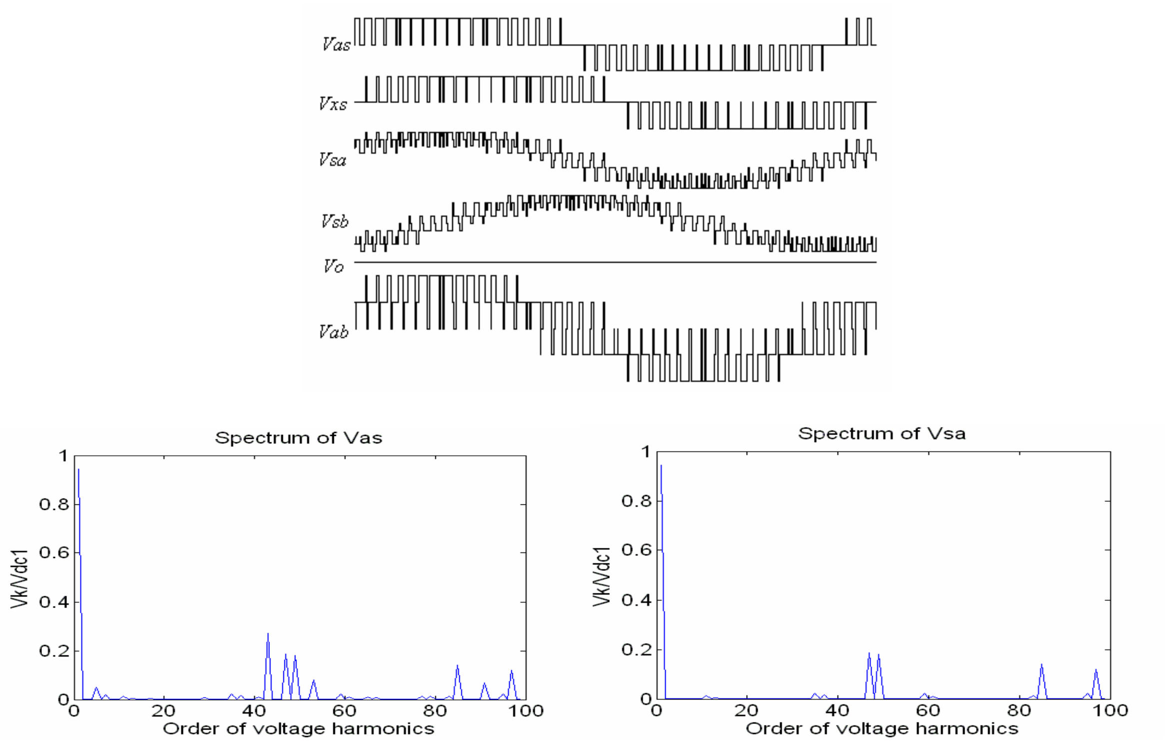


Fig. 5.

The motor phase and line voltages of six-phase drive system with synchronized PWM have symmetry during the whole control range, and its spectra do not include even harmonics and sub-harmonics. The described strategy of control of dual neural-point-clamped inverters provides full common-mode voltage elimination both in each inverter and in the load, which is leading to an increase of the reliability and life span of the drive systems with modulated power converters.

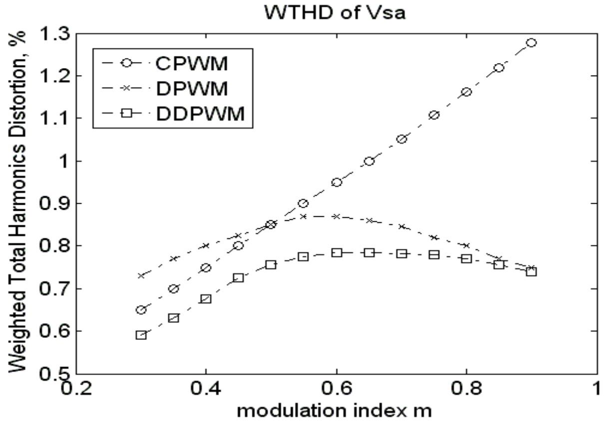


Fig. 6

Fig. 6 presents averaged calculation results of the Weighted Total Harmonics Distortion factor ($WTHD = (1/V_1)(\sum_{k=2}^{1000}(V_k/k)^2)^{0.5}$) versus modulation index m for the useful component V_{sa} of the motor phase voltage of asymmetrical six-phase drive system with dual neutral-point-clamped inverters with continuous (CPWM), discontinuous (DPWM) and “direct-direct” (DDPWM) schemes of synchronized modulation during standard scalar *V/F* control until the zone of overmodulation ($V_{dc1}=V_{dc2}$, $m_1=m_2=m=0.3–0.9$). Average switching frequency of each inverter is equal to F_S=900 Hz for the all presented versions of synchronized PWM.

Results of analysis of spectral composition of the useful component of motor phase voltage show that at low modulation indices Weighted Total Harmonic Distortion factor is better for the drive systems with continuous and “direct-direct” schemes of synchronous PWM, and at the medium and high modulation indices, discontinuous and “direct-direct” versions of synchronized PWM provide the better *WTHD* factor.

The method of synchronized pulsewidth modulations provides also high quality linear control of the fundamental voltage of both three-phase and dual three-phase (six-phase) drive systems on the base of neutral-clamped inverters in the zone of overmodulation [5].

Conclusion. The developed method of synchronised PWM has been applied for control of asymmetrical six-phase drive on the base of dual neutral-point-clamped inverters. Specialized control algorithms provide in this case both full elimination of the alternating common-mode voltages (both in each inverter and in the load), and continuous shock-less synchronization of the output voltage waveforms of two inverters during the whole control range including the zone of overmodulation.

The spectra of the motor phase voltages of asymmetrical dual three-phase systems with synchronized PWM do not contain even harmonics and subharmonics for any ratios (integral or fractional) between the switching and fundamental frequencies of dual converters, which is especially important for drives for high power applications.

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Надійшла 16.03.09