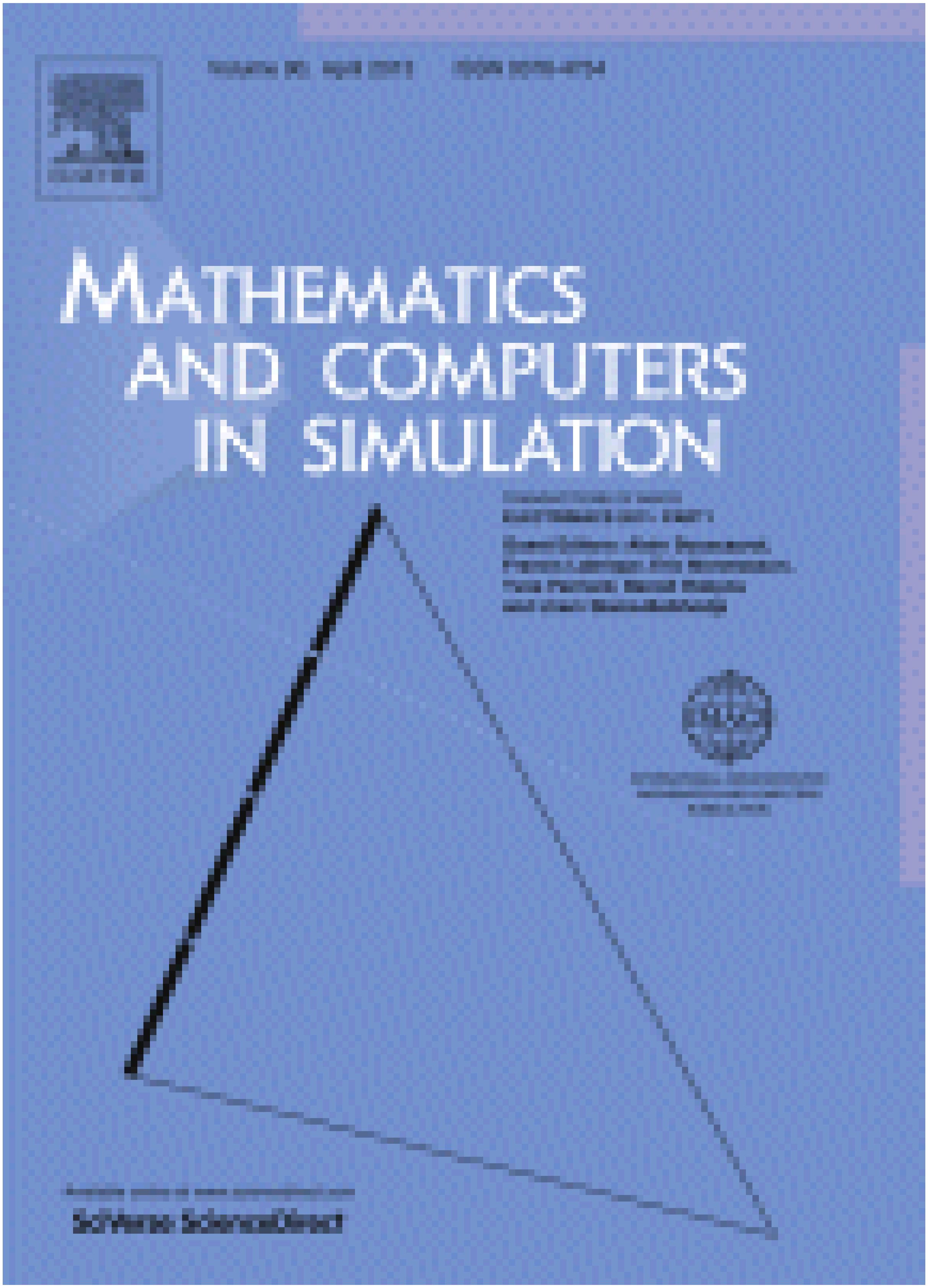
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A simple multi-level space vector modulation algorithm for five-phase open-end winding drives(Article)

Jones, M., Satiawan, I.N.W.

Liverpool John Moores University, School of Engineering, Byrom St, Liverpool L3 3AF, United Kingdom

Abstract

Three-phase open-end winding variable speed drives with dual-inverter supply have been extensively investigated for various applications, including series hybrid powertrains and propulsion motors. The topology is simple to realise while offering a higher number of switching states without the need for capacitor balancing algorithms, when compared to standard multi-level converters. There are very few works which consider the use of multi-phase machines in such topologies. One of the reasons for this is that inclusion of a multi-phase machine leads to exponential increase in the number of possible switching states and so the design of a suitable space vector modulator (SVM) represents a considerable challenge. This paper considers a five-phase open-end winding drive and proposes a relatively simple SVM algorithm, based on the already well understood five-phase two-level drive SVM method. The proposed modulation technique has the advantage of being straightforward to implement and, like its two-level counterpart, is able to generate output voltages with minimum low-order harmonic content. The method generates up to seventeen-level output phase voltage and therefore offers superior harmonic performance when compared to the two-level five-phase topology. The developed scheme is verified via simulation including the dynamic performance of the five-phase machine operating under V/f control and experimentally using a passive load. © 2012 IMACS. Published by Elsevier B.V All rights reserved.

Author keywords

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A simple multi-level space vector modulation algorithm for five-phase open-end winding drives

Martin Jones *, I. Nyoman Wahyu Satiawan

Liverpool John Moores University, School of Engineering, Byrom St, Liverpool L3 3AF, UK

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Abstract

Three-phase open-end winding variable speed drives with dual-inverter supply have been extensively investigated for various applications, including series hybrid powertrains and propulsion motors. The topology is simple to realise while offering a higher number of switching states without the need for capacitor balancing algorithms, when compared to standard multi-level converters. There are very few works which consider the use of multi-phase machines in such topologies. One of the reasons for this is that inclusion of a multi-phase machine leads to exponential increase in the number of possible switching states and so the design of a suitable space vector modulator (SVM) represents a considerable challenge. This paper considers a five-phase open-end winding drive and proposes a relatively simple SVM algorithm, based on the already well understood five-phase two-level drive SVM method. The proposed modulation technique has the advantage of being straightforward to implement and, like its two-level counterpart, is able to generate output voltages with minimum low-order harmonic content. The method generates up to seventeen-level output phase voltage and therefore offers superior harmonic performance when compared to the two-level five-phase topology. The developed scheme is verified via simulation including the dynamic performance of the five-phase machine operating under *V/f* control and experimentally using a passive load.

Keywords: Five-phase; Multi-level; PWM; Open-end winding; Space-vector modulation

1. Introduction

The past few years have witnessed an increasing research effort in both the multi-phase drive and multi-level converter areas [1,12–14]. Multi-level converters are considered as a topology which enhances the quality of the output voltage waveform and enables the construction of a high power converter without the problem of switching series connected semiconductor devices. Additional advantages of the multi-level converter include reduced *dv/dt* and increased fault tolerance.

There are numerous topologies of multi-level converter. The main ones are the neutral point clamped (NPC), the flying capacitor (FC) and the cascaded converters [16,18]. The open-end winding topology, can be considered as an alternative approach to create multi-level load phase voltage waveforms. The equivalence of the topology with a two-level inverter on each side of the stator winding and three-level or four-level single-sided supplied drive (depending

* Corresponding author. Tel.: +44 151 231 2339; fax: +44 151 298 2624.
E-mail address: M.jones2@ljmu.ac.uk (M. Jones).

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on the dc-bus voltage ratio), is shown in terms of performance and created multi-level load phase voltages in [3] for three-phase drives. Three-phase open-end winding dual-inverter fed drive systems are currently under investigation as possible alternative supply solutions in EVs/HEVs [9,20], for electric ship propulsion [11], rolling mills [10].

In applications such as EVs, where dc bus voltage is rather limited, the main reported advantage with respect to the equivalent multi-level single-sided supply is that a machine with a lower current rating can be utilised since the voltage across phases can be higher when two independent batteries are used instead of a single one [8,19]. Furthermore, the additional diodes used in the diode-clamped (NPC) VSI are not needed, leading to a saving in the overall number of components. The problem of capacitor voltage balancing does not exist if the supply is two-level at each winding side.

Multi-phase variable-speed drive systems are currently regarded as another type of potentially viable solutions for the same applications, including EVs/HEVs [13], [2]. A two-level multi-phase VSI is the standard solution, with the star-connected machine winding and an isolated neutral point. Since the advantages of multi-level inverters and multi-phase drives complement each other, it appears to be logical to try to combine them by realising a multi-level multi-phase drive. Currently there are very few examples [7,8,19] of such topologies.

Recently multi-phase drive systems in open-end winding configuration have been developed in [19] and [8], where an asymmetrical six-phase induction motor drive is considered. In [19] the supply is provided by means of two isolated two-level six-phase VSIs. The goal was in essence low-order harmonic elimination/reduction rather than the multi-level operation. As a consequence, the converter is not operated in multi-level mode. The scheme considered in [8] employs four three-phase two-level inverters, with four isolated dc sources, to prevent circulation of zero sequence currents. The SVM control is performed in essence independently for the two three-phase windings, using the nearest three vectors approach (NTV) in conjunction with three-level NPC inverter [4]. The work is focused towards controlling the power sharing between the four converters. Open-end winding five-phase structure is considered in [17], where the machine is supplied using a H-bridge across each winding and a common dc bus. A five-phase drive with a single three-level NPC converter is considered in [7]. The SVM method is complicated, particularly the sector identification, since each 36° sector is partitioned into ten subsectors.

Due to the large number of switching states (1024) available in the five-phase open-end winding configuration, along with the fact that the control must consider both sub-spaces, the development of a suitable SVM method is particularly challenging. This paper develops a relatively simple SVM algorithm suitable for the five-phase open-end winding topology. The modulation of the open-end winding drive is considered from the perspective of a previously developed two-level five-phase SVM technique. In doing so the problem is broken down into one of reduced complexity.

General properties of the five-phase ac motor drives with sinusoidal winding distribution are at first reviewed, along with the previously developed two-level SVM algorithm for a five-phase two-level VSI [6], which uses two large and two medium active space vectors per switching period in order to minimise low-order harmonics. Next, mathematical model of the five-phase open-end winding topology is given, along with mapping of the space vectors that are of interest into the torque-producing 2D plane. The performance of the open-end winding five-phase drive is investigated and verified via simulation and experimental results.

1.1. Two-level five-phase space vector modulation

Prior to considering the SVM schemes for the open-end winding topology, it is beneficial to review the basic relationships which govern the performance of five-phase drives and the corresponding two-level SVM technique for a five-phase VSI. A five-phase machine can be modelled in two 2D sub-spaces, so-called α–β and x–y sub-spaces [6]. It can be shown that, for a machine with near sinusoidal magneto-motive force distribution, only current harmonic components which map into the α–β sub-space develop useful torque and torque ripple, whereas those that map into the x–y sub-space do not contribute to the torque at all [13]. A multi-phase machine with near-sinusoidal magneto-motive force distribution presents extremely low impedance to all non-flux/torque producing supply harmonics and it is therefore mandatory that the supply does not generate such harmonics. What this means is that the design of a five-phase PWM strategy must consider simultaneously both 2D sub-spaces, where the reference voltage, assuming pure sinusoidal references, is in the first plane, while reference in the other plane is zero. Two-level five-phase inverters can generate up to $2^5 = 32$ voltage space vectors with corresponding components in the α–β and x–y sub-spaces shown in Fig. 1. Space vectors are labeled with decimal numbers, which, when converted into binary, reveal the values of the switching functions of each of the inverter legs. Active (non-zero) space vectors belong to three groups in accordance with their magnitudes – small, medium and large space vector groups. The magnitudes are identified with indices s, m,

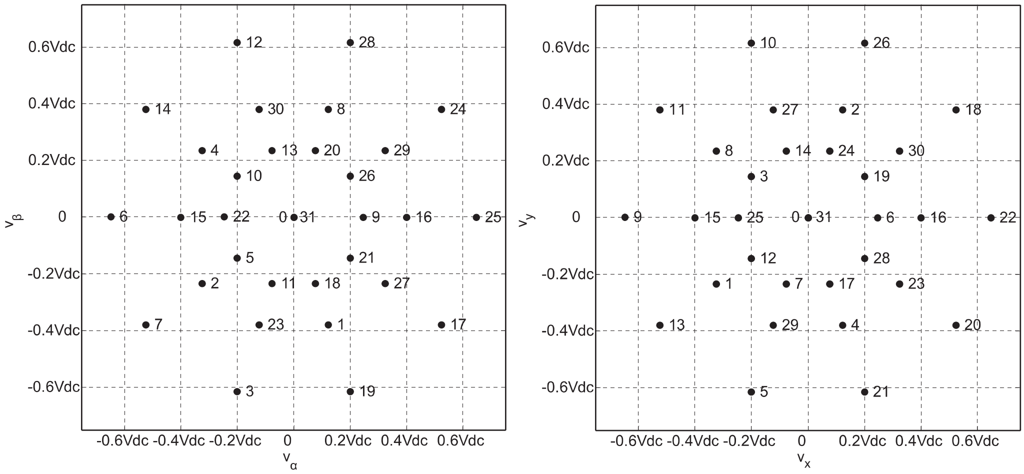

Fig. 1. Two-level five-phase VSI space vectors in the α–β and x–y sub-spaces.

and l and are given as $|\bar{v}_s| = 4/5\ \cos(2\pi/5)V_{dc}$, $|\bar{v}_m| = 2/5V_{dc}$, and $|\bar{v}_l| = 4/5\ \cos(\pi/5)V_{dc}$, respectively. Four active space vectors are required to generate sinusoidal voltages [13,14]. Suppose that the reference space vector in the α–β plane is in sector $s = 1$ as shown in Fig. 2a. Two neighbouring large and two medium space vectors are selected. In order to provide zero average voltage in the x–y plane (Fig. 2b) times of application of active space vectors become [6]:

$$\begin{aligned} t_{al} &= \frac{2\sin(2\pi/5)}{V_{dc}}\sin(s\pi/5 - \vartheta)|\bar{v}^*|t_s \\ t_{am} &= \frac{2\sin(\pi/5)}{V_{dc}}\sin(s\pi/5 - \vartheta)|\bar{v}^*|t_s \end{aligned} \tag{1}$$

$$\begin{aligned} t_{bl} &= \frac{2\sin(2\pi/5)}{V_{dc}}\sin[\vartheta - (s-1)\pi/5]|\bar{v}^*|t_s \\ t_{bm} &= \frac{2\sin(\pi/5)}{V_{dc}}\sin[\vartheta - (s-1)\pi/5]|\bar{v}^*|t_s \end{aligned} \tag{2}$$

where t_s is the switching period, ϑ is the reference position and indices a and b are defined in Fig. 2a. Total time of application of zero space vectors $t_o = t_s - (t_{al} + t_{am} + t_{bl} + t_{bm})$ is equally shared between zero space vectors $\bar{v}_0$ and $\bar{v}_{31}$. The maximum peak value of the output fundamental phase-to-neutral voltage in the linear modulation region is $v_{\max} = V_{dc}/[2\cos(\pi/10)] = 0.525\ V_{dc}$. Switching pattern is a symmetrical PWM with two commutations per each inverter leg.

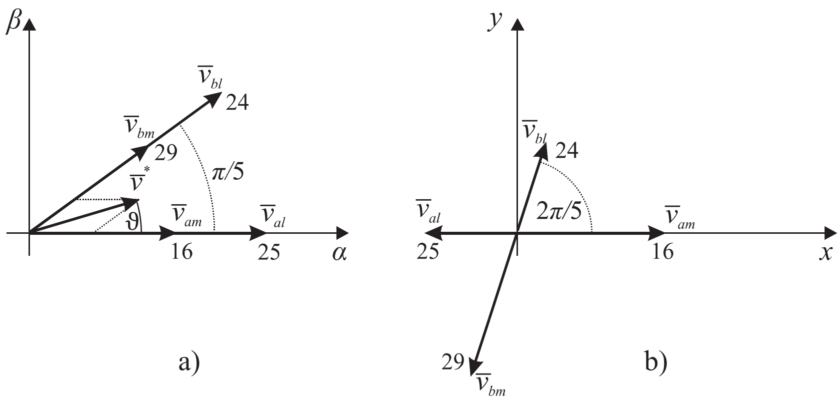

Fig. 2. Principle of calculation of times of application of the active space vectors in the α–β (a) and x–y (b) sub-spaces.

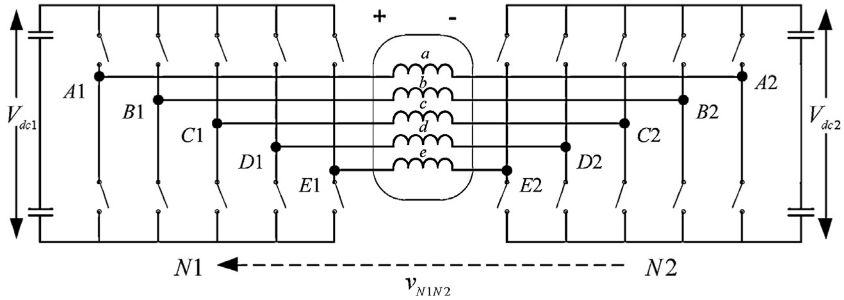

Fig. 3. Five-phase machine with dual two-level inverter supply.

1.2. Five-phase open-end-winding configuration

Fig. 3 illustrates the open-end winding structure, based on utilisation of two two-level five-phase VSIs. The two inverters are identified with indices 1 and 2. Inverter legs are denoted with capital letters, A, B, C, D, E and the negative rails of the two dc links are identified as $N1$ and $N2$. Machine phases are labelled as a, b, c, d, e. Phase voltage positive direction is with reference to the left inverter (inverter 1). Using the notation of Fig. 3, phase voltages of the stator winding can be given as [15]:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \\ v_d \\ v_e \end{bmatrix} = (1/5)\begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix}\begin{bmatrix} v_{A1N1} - v_{A2N2} \\ v_{B1N1} - v_{B2N2} \\ v_{C1N1} - v_{C2N2} \\ v_{D1N1} - v_{D2N2} \\ v_{E1N1} - v_{E2N2} \end{bmatrix} \quad (3)$$

Two isolated dc supplies are assumed so that the common mode voltage (CMV) v_{N1N2} is of non-zero value (the issue of CMV elimination is not addressed here). The resulting space vectors in dual-inverter supply mode will depend on the ratio of the two dc bus voltages. The situation considered further on is the setting $V_{dc1} = V_{dc2} = V_{dc}/2$, which gives the equivalent of single-sided three-level supply. Here V_{dc} stands for the equivalent dc voltage in single-sided supply mode. By considering the dc bus voltages settings and by examination of (3) it can be determined that the topology can generate up to 17 levels in the load phase voltages [15]. The increased number of load phase voltage levels is a consequence of the much greater number of switching states and voltage space vectors generated by the converter, when compared to the single-sided supply mode.

Space vectors of phase voltages in the two sub-spaces are determined with:

$$\begin{aligned} \bar{v}_{\alpha-\beta} &= (2/5)(v_a + \underline{a}v_b + \underline{a}^2v_c + \underline{a}^3v_d + \underline{a}^4v_e) \\ \bar{v}_{x-y} &= (2/5)(v_a + \underline{a}^2v_b + \underline{a}^4v_c + \underline{a}^6v_d + \underline{a}^8v_e) \end{aligned} \quad (4)$$

where $\underline{a} = \exp(j2\pi/5)$. Using (3) and (4), one gets:

$$\begin{aligned} \bar{v}_{\alpha-\beta} &= \bar{v}_{\alpha-\beta(A1B1C1D1E1)} - \bar{v}_{\alpha-\beta(A2B2C2D2E2)} \\ \bar{v}_{x-y} &= \bar{v}_{x-y(A1B1C1D1E1)} - \bar{v}_{x-y(A2B2C2D2E2)} \end{aligned} \quad (5)$$

When developing a suitable SVM strategy for the dual-inverter supply and considering (5), it seems logical to adapt the two-level SVM method for five-phase VSI of [6] accordingly. Considering that the two-level SVM method uses only large and medium active vectors (4 active vectors and two zero vectors) during each switching period and these can now be applied from each side, there are nine possible vector combinations, listed in Fig. 4. The nine vector combinations result in a total of 131 phase voltage space vector positions [15]. Since each inverter uses a total of 20 active vectors and two zero vectors, there are $22 \times 22 = 484$ possible switching states for the duel inverter configuration. Hence, there are 353 redundant switching states. The space vector lengths and positions, in the α–β sub-space, generated by these vector combinations, are presented in Fig. 4 (zero–zero combination is omitted). The high level of redundancy, which exists,

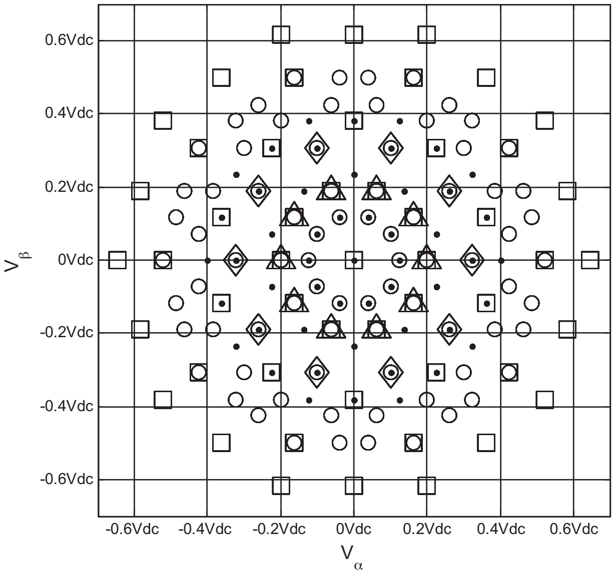

Fig. 4. Space vectors in α–β plane, created by *l–l* (□), *m–m* (●), *m–l, l–m* (◯), *l–z, z–l* (◊), *m–z, z–m* (△) combinations.

offers great scope for optimizing the performance of the converter. The development of such algorithms is beyond the scope of this paper and is postponed for further work.

2. Unequal reference sharing technique

The proposed SVM scheme, shown in Fig. 5, uses two identical two-level modulators. The voltage reference applied to the modulators is apportioned according to the modulation index $M = v^*/(0.5V_{dc})$. The modulation indices of the individual inverters are $M_1 = v_1^*/(0.5V_{dc1})$, $M_2 = v_2^*/(0.5V_{dc2})$. Inverter 1 only is operated up to the point when $M = 0.525$ ($M_1 = 1.05$). Hence the converter operates in two-level mode, since inverter 2 is not modulated and the inverter is locked in a zero state, 11111 or 00000, forming a neutral point. When $M > 0.525$, inverter 1 is held at

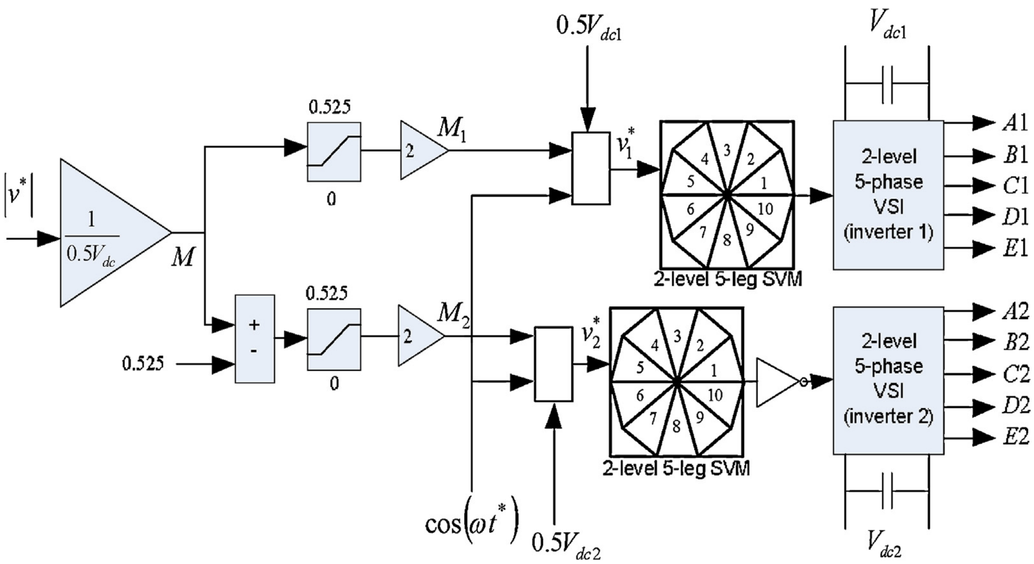

Fig. 5. Unequal reference sharing scheme.

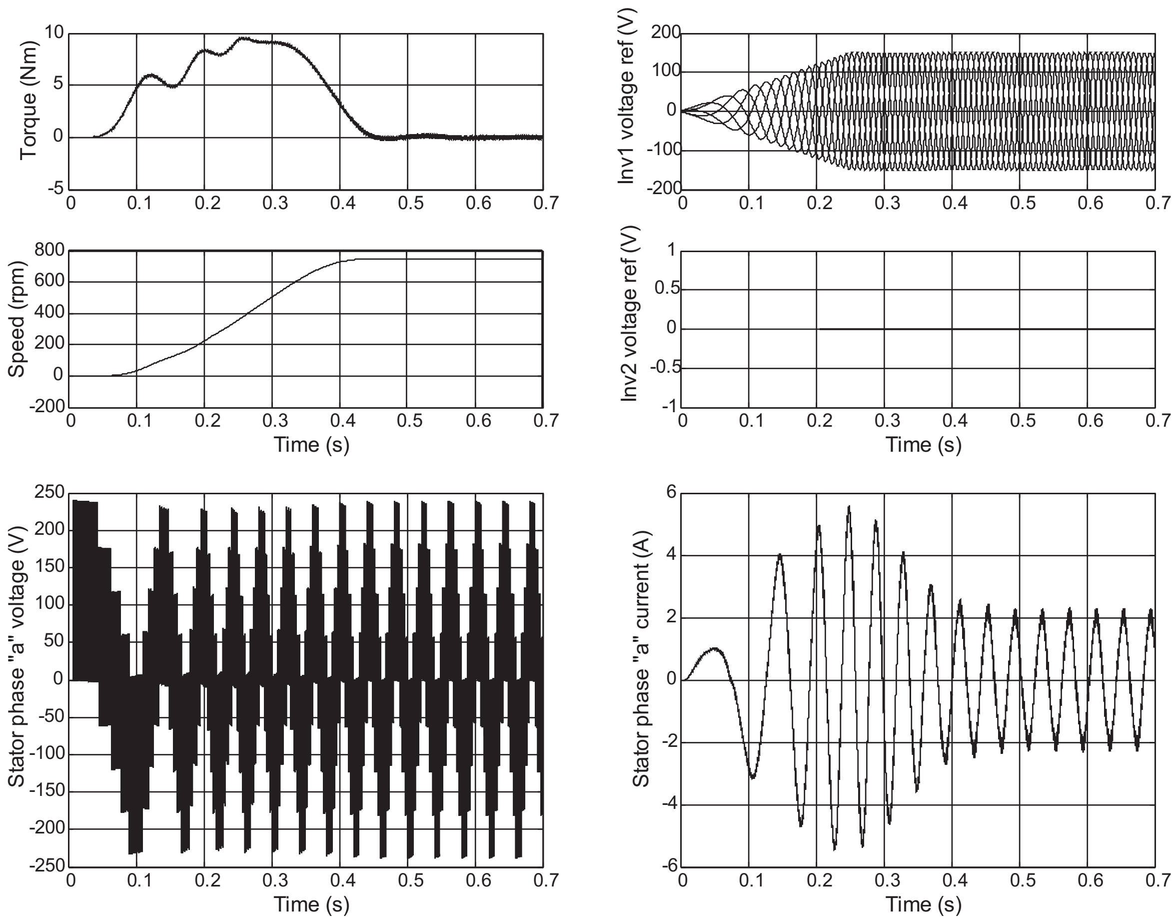

Fig. 6. Motor acceleration under *V/f* control ($M = 0.5$, 25 Hz): speed, torque, inverter voltage references, stator phase "*a*" voltage and current.

$M_1 = 1.05$ (its maximum modulation index) and inverter 2 output is modulated. These constraints can be expressed as:

$$
\begin{array}{ll}
0 \le M \le 0.525 & \begin{cases} M_1 = 2M \\ M_2 = 0 \end{cases} \\
0.525 < M \le 1.05 & \begin{cases} M_1 = 1.05 \\ M_2 = 2(M - 0.525) \end{cases}
\end{array} \tag{6}
$$

3. Simulation verification

In order to verify the performance of the drive, a series of detailed simulations were undertaken using PLECS software. Inverter dead-time is set to 6 μs and the switching frequency of each inverter is fixed at 2 kHz. The phase variable model of the five-phase machine with, sinusoidal mmf distribution, [5,13] is used and the drive is operated in open-loop *V/f* mode. The voltage reference profile is such that the supply frequency of the machine is ramped from 0 to 50 Hz in 0.5 s. At the operating frequency of 52.5 Hz the maximum modulation index is reached ($M = 1.05$), voltage boost is not applied. The dc bus of each inverter is 300 V, giving an effective dc bus voltage of 600 V when $M > 0.525$.

The acceleration transient is presented in Figs. 6 and 7 for $M = 0.5$ (25 Hz) and $M = 0.8$ (40 Hz), respectively. It can be seen in Fig. 6 that no voltage reference is applied to inverter 2 when $M = 0.5$ and so the drive operates in

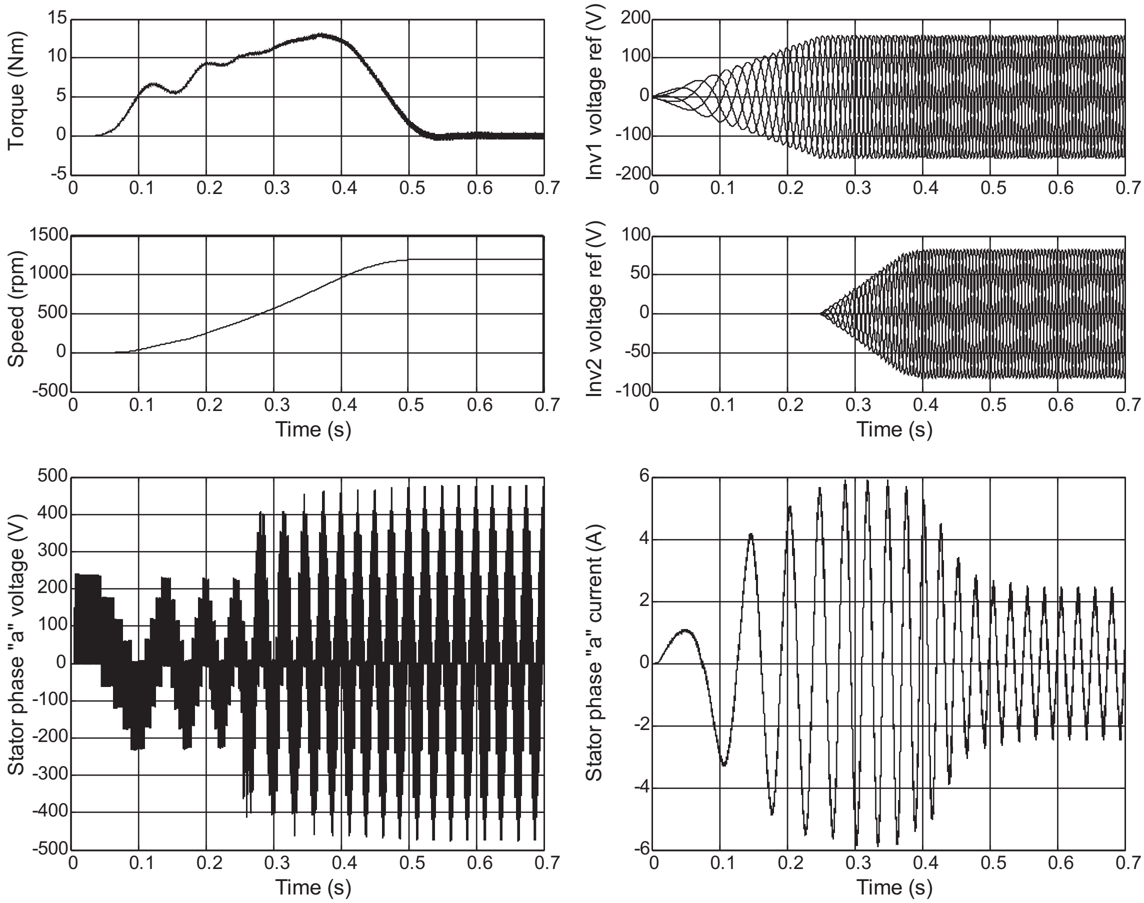

Fig. 7. Motor acceleration under *V/f* control ($M = 0.8$, 40 Hz): speed, torque, inverter voltage references, stator phase "*a*" voltage and current.

two-level mode as evidenced by the load phase voltage waveform comprising of 9 levels. Fig. 7 shows that, as soon as $M > 0.525$ (at $t = 0.25$ s) inverter 2 is modulated, with inverter 1 operating at the maximum modulation index ($M_1 = 1.05$). At $t = 0.4$ s the reference frequency is reached and $M_2 = 0.55$. The phase currents remain sinusoidal throughout the transient.

Figs. 8 and 9 show the steady state performance of the drive when $M = 0.5$ and $M = 0.8$ respectively. When $M = 0.5$ the steady-state phase voltage contains only nine levels and has a peak value of 240 V, however the spectrum is much improved when compared with its single sided two-level equivalent due to the 50% reduction in the effective dc bus voltage when compared to the equivalent two-level five-phase drive. The phase current waveform and spectrum indicate a minimal low-order harmonic content with some very small third and seventh harmonics present due to the inverter dead-time. This effect is particularly noticeable in the x–y sub-space where the third and seventh harmonics map into. The α–β sub-space is virtually clear of low-order harmonics. When $M = 0.8$ the drive is operating in multi-level mode as evidenced by the steady-state load phase voltage comprising more than 9 levels. The phase voltage and current spectra again indicate minimal low-order harmonics and the target fundamental voltage and current have been met. The current projection in the x–y plane contains harmonics created by the inverter dead time as well as some switching harmonics which also map into this plane. The torque/flux producing α–β plane is virtually free of low-order harmonics.

The switching trajectories of the converter and the switching state of each inverter, for the case when $M = 0.8$, are shown in Fig. 10 for 0° and 9° of the reference position in sector 1 of the α–β plane. The vectors are numbered in the same manner as in Fig. 1, the upper being inverter 2 and the lower inverter 1. When the reference is along the sector border (every 36°) only five active vectors are used, whereas nine active vectors are used otherwise. Further

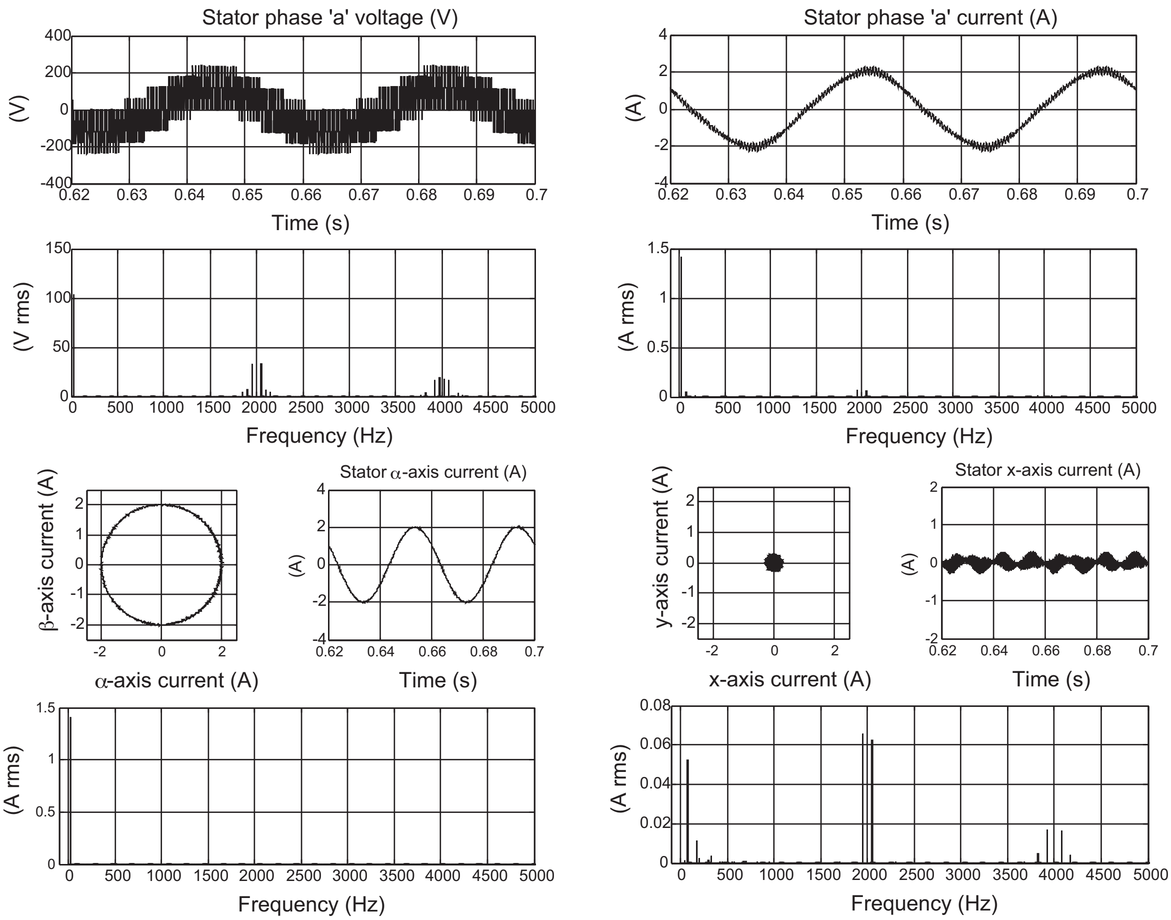

Fig. 8. Motor steady-state waveforms ($M = 0.5$, 25 Hz): phase "*a*" voltage and current with spectrum, α-axis and x-axis current waveforms with spectrum and current projection in the α–β and x–y sub-spaces.

simulations show that different active vectors are used as the reference moves through the sector, hence an equivalent single SVM would require a large look-up table containing the switching sequences.

4. Experimental verification

The proposed modulation technique is further verified using two custom built five-phase two-level VSIs and an *R-L* load, where the resistive part is a bulb. The inverters are controlled using a dSPACE DS1006 processor board. The dSPACE module is connected to two-level VSIs via a dSPACE DS5101 digital waveform output board. Both VSIs are fed with isolated three-phase 70.7 V rms line-to-line voltage, through diode bridge rectifiers, giving approximately 100 V dc bus voltage at each inverter. The experimental set-up is shown in Fig. A1. The load voltage is controlled using the same *V/f* control law as described in the simulations. The switching frequency of each inverter is 1 kHz and the switch dead time is approximately 6 μs. The phase voltages are measured using a deep memory (1 M samples) digital oscilloscope in differential mode and a voltage divider. The spectra are calculated using MATLAB software.

Fig. 11 depicts the experimental results obtained when $M = 0.5$ and $M = 0.8$. When $M = 0.5$ it can be seen that the drive operates in two-level mode and the effective dc bus is approximately 100 V. The phase voltage comprises nine levels and the target fundamental has been approximately met. Performance of the drive when $M = 0.8$ is presented in Fig. 11b. The drive now utilizes both inverters and so the effective dc bus is approximately 200 V. Upon close inspection seventeen voltage levels can be identified which matches well with the simulation results (Fig. 9). In both cases the currents contain very little low-order harmonics.

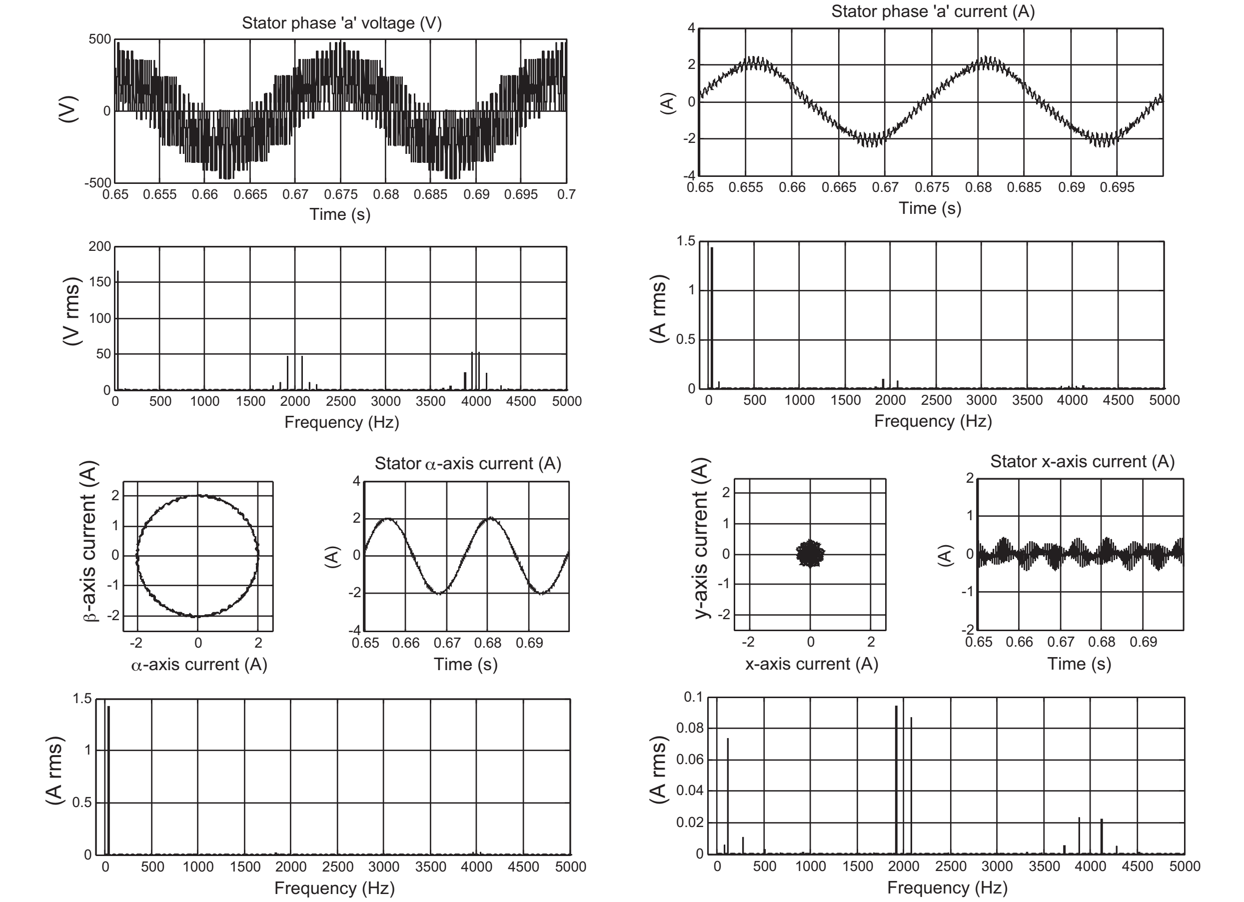

Fig. 9. Motor steady-state waveforms ($M = 0.8$, 40 Hz): phase "*a*" voltage and current with spectrum, *α*-axis and *x*-axis current waveforms with spectrum and current projection in the *α*–*β* and *x*–*y* sub-spaces.

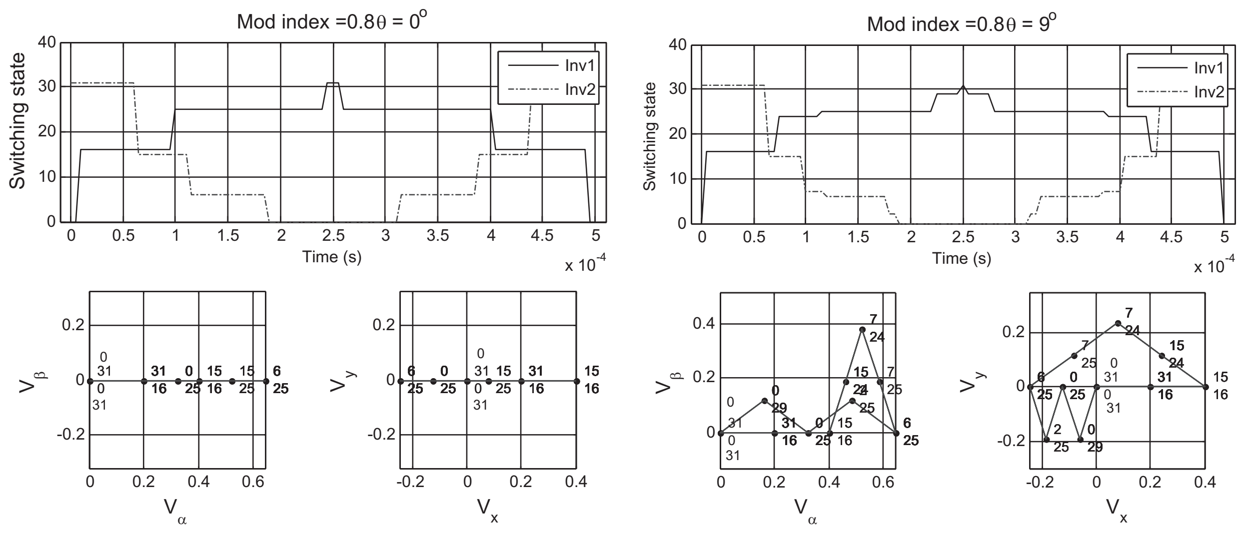

Fig. 10. Inverter switching trajectories in the *α*–*β* and *x*–*y* sub-spaces for $M = 0.8$ and reference angular positions of 0° and 9° in the *α*–*β* plane.

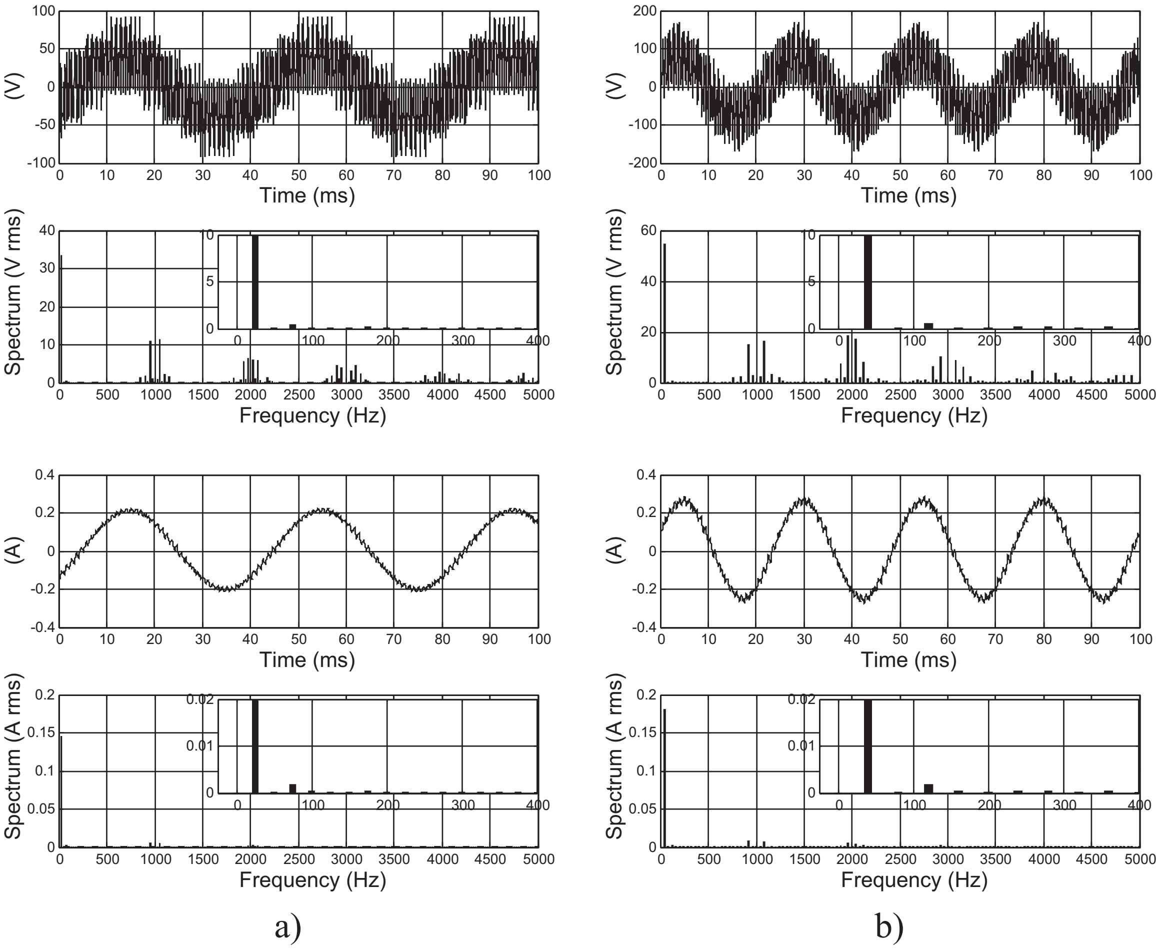

Fig. 11. Experimental results: load phase voltage and current, $M = 0.5$, 25 Hz (a) and $M = 0.8$, 40 Hz (b).

5. Conclusion

This paper has presented a SVM method for the dual-inverter five-phase open-end winding topology, which is relatively easy to implement. The scheme utilizes two standard five-phase two-level SVM modulators, one for each inverter, and apportions the voltage reference to each two-level modulator so that when $M \leq 0.525$ only one inverter output is modulated. When $M > 0.525$ both inverter outputs are modulated, with inverter 1 held at its maximum modulation index ($M_1 = 1.05$). It can be argued that the presented method does not achieve true multi-level operation since the zero vectors are always applied even when $M > 0.525$. Nevertheless the method does achieve more than 9 levels of the output phase voltage and offers significant improvement in harmonic performance when compared to the five-phase two-level counterpart. The performance of the drive has been verified using detailed simulations and an experimental prototype.

Appendix A.

Fig. A1

References

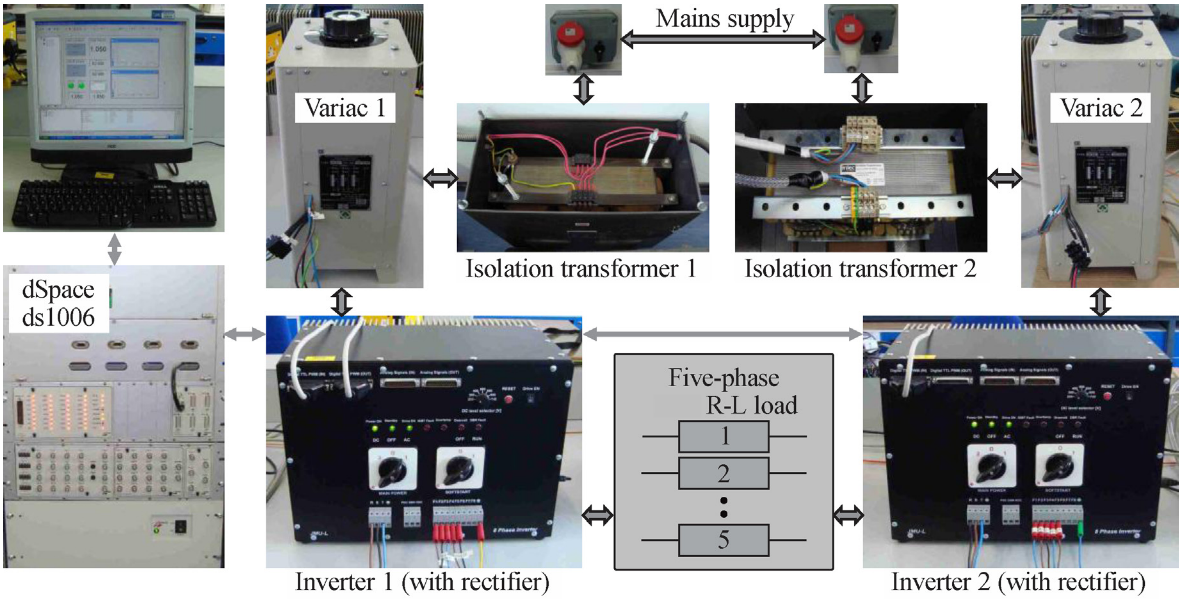

Fig. A1. A1 Experimental setup of the open-end winding five-phase supply topology.

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