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# A SIMPLE MULTI-LEVEL SPACE-VECTOR MODULATION ALGORITHM FOR FIVE-PHASE OPEN-END WINDING DRIVES

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**Abstract -** 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. The overwhelming majority of work is however restricted to the three-phase electric machinery. 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 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.

**Keywords** – Multi-level inverters, Multi-phase drives, Space-vector modulation, Open-end winding

## 1. INTRODUCTION

The past few years have witnessed an increasing research effort in both the multi-phase drive and multi-level converter areas [1]-[4]. 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 [5]-[6]. Among the cascaded converters, the dual two-level inverter configuration has received growing attention due to its simple structure [7]. Typically, three-phase VSIs are utilised. Application of such a dual-inverter supply enables drive operation with voltage waveform equivalent to the one obtainable with a three-level VSI in single-sided supply mode. Three-phase open-end winding dual-inverter fed drive systems are currently considered as possible alternative supply solutions in EVs/HEVs [8]-[9], for electric ship propulsion [10], rolling mills [11], etc.

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 [8,9]. 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 [2], [12]. 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 [13]-[15] of such topologies.

The only known examples where multi-phase drive systems in open-end winding configuration have been developed are [13] and [14] where an asymmetrical six-phase induction motor drive is considered. In [13] 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 [14] 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 [7]. The work is focused towards controlling the power sharing between the four converters. A five-phase drive with a single three-level NPC converter is considered in [15]. The SVM method is complicated, particularly the sector identification, since each 36 degree sector is partitioned into ten subsectors.

This paper develops a simple SVM algorithm based on the previously developed SVM method for two-level five-phase converters. 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 [16], 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 cascaded topology is given, along with mapping of the space vectors that are of interest into the torque-producing 2D sub-space. The performance of the open-end winding five-phase drive is investigated and verified via simulation.

## 2. TWO-LEVEL FİVE-PHASE SVM

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 planes, so-called *α-β* and *x-y* sub-spaces [16]. It can be shown that 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. 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*, 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 [1], [2]. Suppose that the reference space vector in the *α-β* plane is in sector $s=1$ (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 [16]:

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

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

where $t_s$ is the switching period, $\vartheta$ 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 $v_{\max} = V_{dc}/[2\cos(\pi/10)] = 0.525V_{dc}$. Switching pattern is a symmetrical PWM with two commutations per each inverter leg.

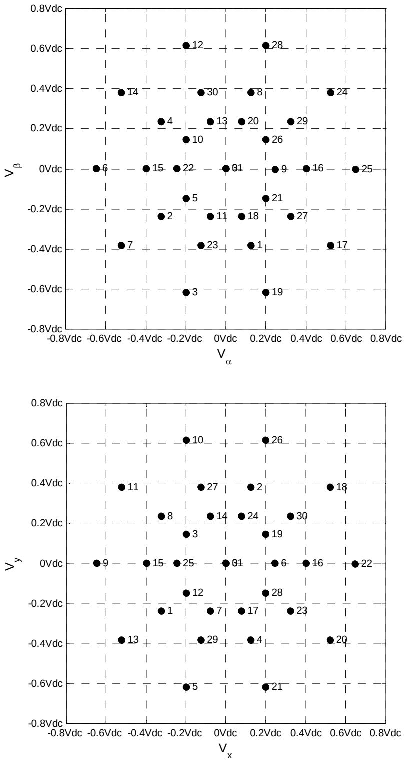

Fig. 1. Two-level five-phase VSI space vectors in the $\alpha$–$\beta$ and *x-y* planes.

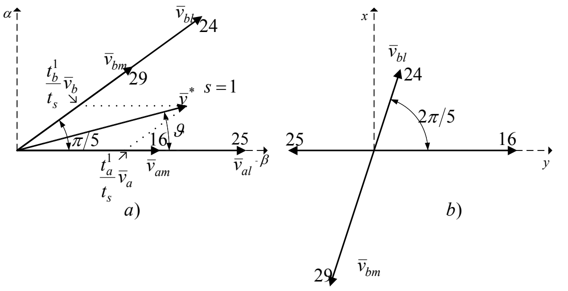

Fig. 2. Principle of calculation of times of application of the active space vectors in the $\alpha$–$\beta$ (a) and *x-y* (b) planes.

## 3. FIVE-PHASE OPEN-END DRIVE 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 *N*1 and *N*2. 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 [17]:

$$\begin{aligned} v_a &= v_{A1N1} + v_{N1N2} - v_{A2N2} \\ v_b &= v_{B1N1} + v_{N1N2} - v_{B2N2} \\ v_c &= v_{C1N1} + v_{N1N2} - v_{C2N2} \\ v_d &= v_{D1N1} + v_{N1N2} - v_{D2N2} \\ v_e &= v_{E1N1} + v_{N1N2} - v_{E2N2} \end{aligned} \tag{3}$$

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. Since in five-phase case single-sided supply gives nine levels in the phase voltages, it is expected that in five-phase case with dual-inverter supply there will be up to 17 levels in the phase voltage. The increased number of 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 planes are determined with

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

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

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

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 [14] accordingly. Considering that the two-level SVM method uses only large and medium active vectors during each switching period and these can now be applied from each side, there are nine possible vector combinations. The nine vector combinations result in a total of 131 phase voltage space vector positions. Since there are 22×22 = 484 possible switching states then 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, offers great scope for optimising the performance of the converter. The development of such algorithms is beyond the scope of this paper and is postponed for further work.

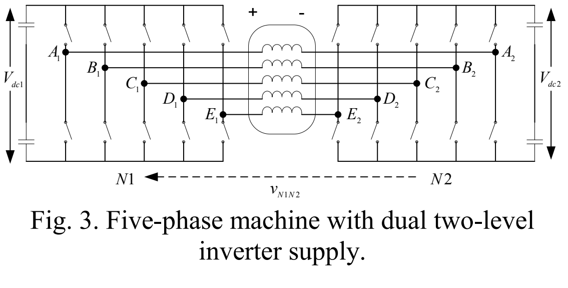

Fig. 3. Five-phase machine with dual two-level inverter supply.

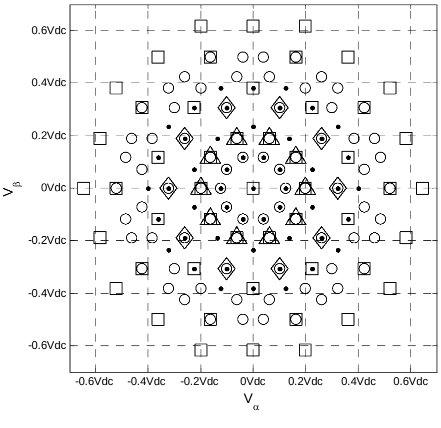

Fig. 4. Space vectors in *α-β* plane, created by *l-l* (□), *m-m* (●), *m-l, l-m* (○), *l-z, z-l* (◊), *m-z, z-m* (Δ) combinations.

The proposed SVM scheme, shown in Fig. 5, uses two identical two-level modulators. However, 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 output is not modulated and the VSI switches between zero states 11111 and 00000. When $M > 0.525$, inverter 1 is held at $M_1 = 1.05$ and inverter 2 output is also modulated. These constraints can be expressed as:

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

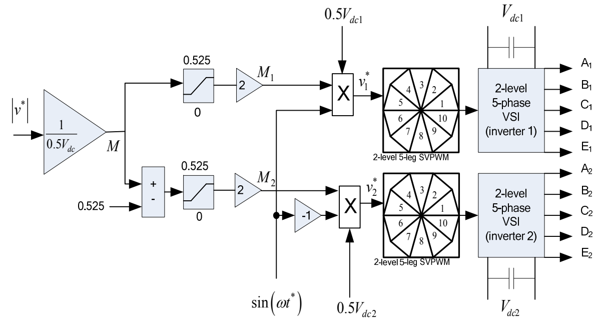

Fig. 5. Unequal reference sharing scheme.

## 4. SIMULATION VERIFICATION

In order to verify the drive's performance a series of detailed simulations were undertaken. The phase variable model of the five-phase machine [18] 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 zero to 50 Hz in 0.5s. At the operating frequency of 50Hz the maximum modulation index is reached ($M = 1.05$), voltage boost is not applied. The switching frequency of each inverter is set to 2 kHz and the dc link is 300 V, giving an effective dc link voltage of 600V when $M$>0.525.

The acceleration transient is presented in Figs. 6 and 7 for 25Hz ($M = 0.525$) and 40Hz ($M = 0.84$), respectively. It can be seen in Fig. 6 that no voltage reference is applied to inverter 2 when $M = 0.525$ and so the drive operates in two-level mode. For this reason the steady-state phase voltage contains only nine levels however, the spectrum is much improved when compared with its single sided two-level equivalent due to the 50% reduction in the effective dc link voltage. 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 $M_2 = 0.63$. The drive is operating in multi-level mode and the steady-state phase voltage now comprises 17 levels. The phase voltage spectra indicate no unwanted low-order harmonics and the target fundamental voltages have been met in both cases.

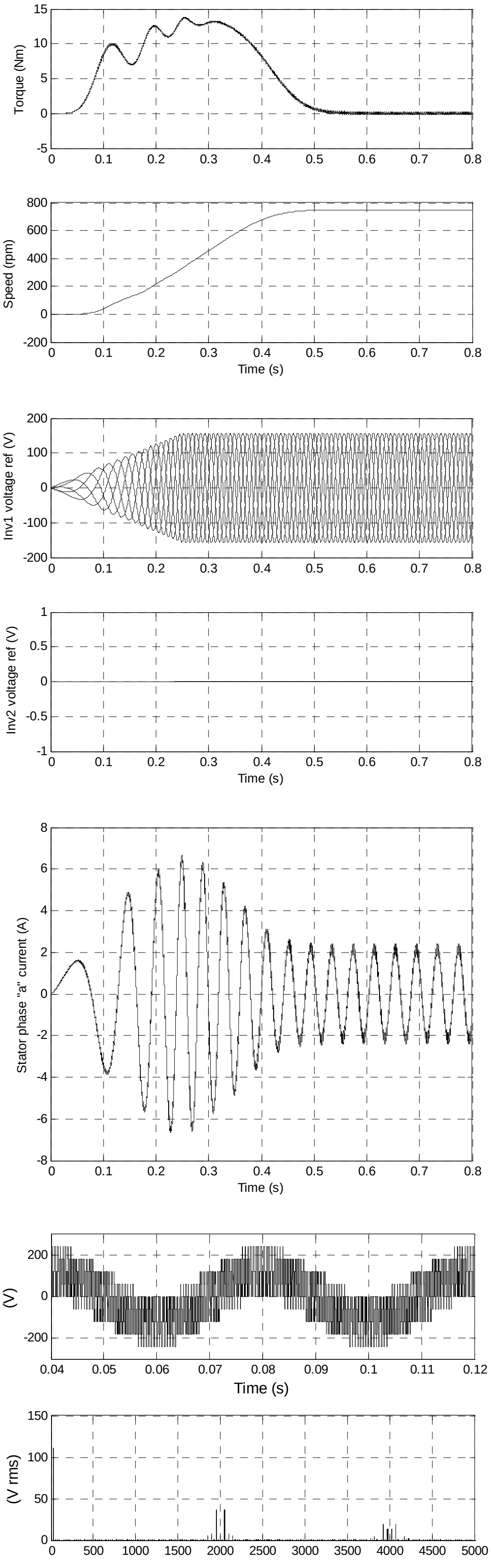

Fig. 6: Motor acceleration under *V/f* control (ref. 25Hz, $M = 0.525$): speed, torque, inverter voltage references, stator current and steady-state phase voltage waveform with spectrum.

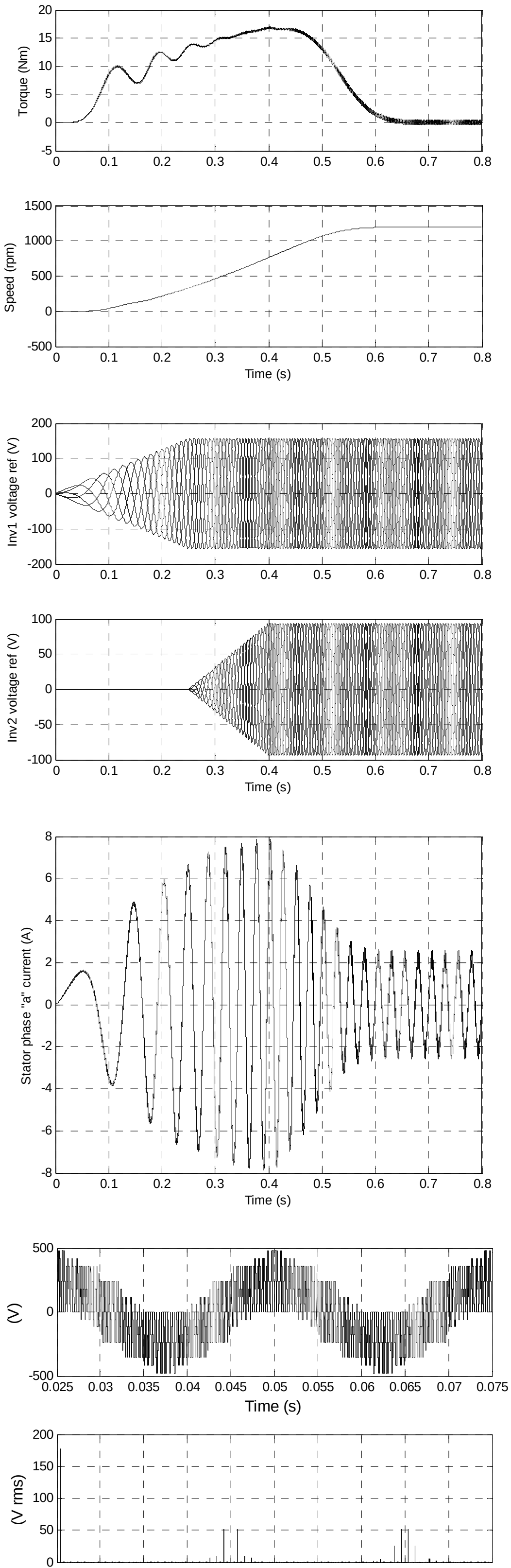

Fig. 7: Motor acceleration under *V/f* control (ref. 40Hz, $M = 0.84$): speed, torque, inverter voltage references, stator current and steady-state phase voltage waveform with spectrum.

The switching trajectories of the converter and the switching state of each inverter, for the case when $M = 0.84$, are shown in Fig. 8 for 0° and 9° of the reference position in sector 1 of the $\alpha$–$\beta$ 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 simulations show that different active vectors are used as the reference moves through the sector, hence an equivalent single SVM would require a large number of look-up tables.

## 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 ($M_1 = 1.05$).

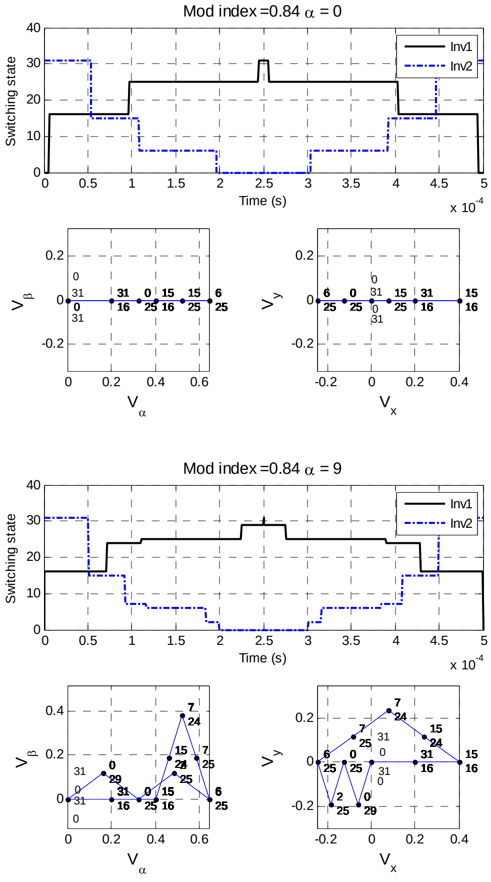

Fig. 8: Inverter switching trajectories in the $\alpha$–$\beta$ and $x$-$y$ planes for $M = 0.84$ and reference angular positions of 0° and 9° in the $\alpha$–$\beta$ plane.

The performance of the five-phase open-end winding drive, using the developed SVM method, has been verified by simulation.

## 6. REFERENCES

[1] E. Levi, R. Bojoi, F. Profumo, H. Toliyat, S. Williamson, Multi-phase induction motor drives: A technology status review, IET Electr. Power Appl., vol. 1, no. 4, pp. 489-516, July 2007.

[2] E. Levi, Multi-phase machines electric machines for variable-speed applications, IEEE Trans. on Ind. Elec., vol. 55, no. 5, pp. 1893-1909, 2008.

[3] H. Abu-Rub, J. Holtz, J. Rodriguez, G. Baoming, Medium-voltage multilevel converters – State of the art, challenges, and requirements in industrial applications, IEEE Trans. on Ind. Elec., vol. 57, no. 8, pp. 2581-2596, 2010.

[4] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. G. Franquelo, B. Wu, J. Rodriguez, M. A. Perez, J. I. Leon, Recent advances and industrial applications of multi-level converters, IEEE Trans. on Ind. Elec., vol. 57, no. 8, pp. 2553-2580, 2010.

[5] S. Lu, S. Mariethoz, K. A. Corzine, Asymmetrical cascade multi-level converters with noninteger or dynamically changing DC voltage ratios: Concepts and modulation techniques, IEEE Trans. on Ind. Appl., vol. 57, no. 7, pp. 1815-1824, 2010.

[6] B.P. McGrath, T.A. Meynard, G. Gateau, D.G. Holmes, Optimal Modulation of Flying Capacitor and Stacked Multicell Converters Using a State Machine Decoder, IEEE Trans. on Power elec., vol.22, no.2, pp.508-516, 2007.

[7] D. Casadei, G. Grandi, A. Lega, C. Rossi, Multi-level operation and input power balancing for a dual two-level inverter with insulated dc sources, IEEE Trans. on Ind. Appl., vol. 44, no. 6, pp. 1815-1824, 2008.

[8] C. Rossi, G. Grandi, P. Corbelli, D. Casadei, Generation system for series hybrid powertrain based on dual two-level inverter, in Proc. European Power Electronics and Applications Conf. EPE, Barcelona, Spain, CD-ROM, 2009.

[9] G. Griva, V. Oleschuk, F. Profumo, Hybrid traction drive with symmetrical split phase motor controlled by synchronised PWM, Int. Symposium on Power Electronics, Electrical. Drives, Automation and Motion SPEEDAM, Ischia, Italy pp. 1033-1037, 2008.

[10] X. Kou, K. A. Corzine, M. W. Wielebski, Overdistension operation of cascaded multi-level inverters, IEEE Trans. on Ind. Appl., vol. 42, no. 3, pp. 817-824, 2006.

[11] Y. Kawabata, M. Nasu, T. Nomoto, E. C. Ejiogu, T. Kawabata, High-efficiency and low acoustic noise drive system using open-winding AC motor and two space-vector-modulated inverters, IEEE Trans. on Ind. Elec., vol. 49, no. 4, pp. 783-789, 2002.

[12] A. Bruyere, L. De Sousa, B. Bouchez, P. Sandulescu, X. Kestelyn, E. Semail, A multiphase traction/fast-battery-charger drive for electric or plug-in hybrid vehicles: Solutions for control in traction mode, Proc. IEEE Vehicle Power and Propulsion Conf. VPPC, Lille, France, CD-ROM paper 95-86315, 2010.

[13] K. K. Mohapatra, K. Gopakumar, A novel split phase induction motor drive without harmonic filters and with linear voltage control for the full modulation range, EPE Journal, vol. 16, no. 4, pp. 20-28, 2006.

[14] G. Grandi, A. Tani, P. Sanjeevikumar, D. Ostojic, Multi-phase multi-level AC motor drive based on four three-phase two-level inverters, Int. Symposium on Power Electronics, Electrical Drives, Automation and Motion SPEEDAM, Pisa, Italy pp. 1768-1775, 2010.

[15] L. Gao, J. E. Fletcher, A space vector switching strategy for three-level five-phase inverter drives, IEEE Trans. on Ind. Elec., vol. 57, no. 7, pp. 2332-2343, 2010.

[16] D. Dujic, M. Jones, E. Levi, Generalized space vector PWM for sinusoidal output voltage generation with multi-phase voltage source inverters, Int. J. Ind. Elec. and Drives, vol. 1, no. 1, pp. 1-13, 2009.

[17] E. Levi, M. Jones, W. Satiawan, A multi-phase dual inverter supplied structure for electric and hybrid electric vehicles, Proc. IEEE Vehicle Power and Propulsion Conf., VPPC, Lille, France, CD-ROM paper 95-45630, 2010.

[18] O. Đorđević, N. Bodo and M. Jones, Model of an induction machine with an arbitrary phase number in MATLAB\SIMULINK for educational use, Proc. Int. Universities Power Engineering Conf. UPEC, Cardiff, UK, CD-ROM, 2010.