# 3.A Three-level Five-phase Space-vector Modulation Algorithm Based on the Decomposition Method(IEMDC2011)

*by* Metta Savitri

---

**Submission date:** 13-Apr-2023 07:19AM (UTC-0500)
**Submission ID:** 2063404578
**File name:** ation_Algorithm_Based_on_the_Decomposition_Method_IEMDC2011.pdf (473.28K)
**Word count:** 4826
**Character count:** 23649

2011 IEEE International Electric Machines & Drives Conference (IEMDC)

# A Three-level Five-phase Space-vector Modulation Algorithm Based on the Decomposition Method

M.Jones, I.N.Satiawan, E.Levi
School of Engineering
Liverpool John Moores University
Liverpool L3 3AF
UNITED KINGDOM
*M.Jones2@ljmu.ac.uk*

***Abstract* – Open-end winding variable speed drives with dual-inverter supply have been extensively investigated for various applications, including series hybrid power-trains 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 decomposition of the three-level space vector decagon into a number of two-level decagons. The proposed modulation technique has the advantage of being relatively simple to implement. The method activates up to fifteen phase voltage levels and produces output voltages with minimum low order harmonic content. Despite the simplicity of the method, the THD of the output voltages is improved, compared to the previously proposed methods. The developed scheme is verified via simulation and the harmonic performance is analysed.**

## I. INTRODUCTION

Multi-level and multi-phase voltage source inverters have been attracting increasing research interest recently due to their ability to overcome voltage and current limitations of power semiconductors and their inherent ability to tolerate faults [1-3]. Multi-level voltage source inverters (VSIs) are considered as a topology which enhances the quality of the output voltage waveform, reduces $dv/dt$ and enables the construction of a high power converter without the problem of switching series-connected semiconductor devices. There are numerous configurations of multi-level converters, the main ones being the neutral point clamped (NPC), the flying capacitor (FC) and the cascaded converters [4].

Among the cascaded converters, the dual two-level inverter configuration has received growing attention due to its simple structure, since the additional diodes used in the diode-clamped (NPC) VSI are not needed, leading to a saving in the overall number of components. Furthermore, the issue of proper capacitor voltage balancing does not exist if the supply is two-level at each winding side. 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 [5]. Such drives are being considered as alternative supply solutions in EVs/HEVs [6]-[7], for electric ship propulsion [8] and rolling mills [9].

Due to their well known advantages [1], multi-phase drives have also been considered for similar applications as the multi-level drives. As a consequence some researchers have recently begun investigating the benefits of combining both technologies [10-16]. The only known examples where multi-phase drive systems in open-end winding configuration have been developed are [15, 16] where an asymmetrical six-phase induction motor drive is considered. In [16] the supply is provided by means of two isolated two-level six-phase VSIs. The goal was, in essence, low-order harmonic reduction rather than the multi-level operation. As a consequence, the converter is not operated in multi-level mode. The scheme considered in [15] 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 the same way as a standard three-level three-phase converter, using the nearest three vectors approach (NTV) in conjunction with three-level NPC inverter [8]. The work is focused towards controlling the power sharing between the four converters.

The remaining literature is primarily centred on the five-phase NPC VSI fed drive [10-14]. The first SVM techniques for multiphase VSIs were based on the simple extension of the three-phase multilevel SVM approaches, so that only the three vectors, nearest to the reference, were utilised. Such an extension from the three-phase to five-phase system, that divides each sector into four equal triangles, is given for three-level inverter in [11] where an optimal SVM switching strategy, based on modified discrete PSO, is presented. In principle, the number of applied vectors must equal the number of phases [1]. Utilisation of three instead of five space vectors during the switching period disregards this basic rule; consequently only the first plane of the multiphase system is controlled. Hence numerous low-order harmonics are generated, which map into the second plane. The NTV method is also used in [12]. A SVM method which controls both planes has been developed in [13] for the three-level NPC VSI supplied five-phase drive. The SVM method is complicated, particularly the sector identification, since each 36 degree sector is partitioned into ten subsectors. A somewhat different approach to the SVM of multi-level

978-1-4577-0061-3/11/$26.00 ©2011 IEEE

multi-phase system is given for a general case of an *l*-level, *n*-phase VSI in [14]. The algorithm is based on the considerations of the multidimensional (*n*-dimensional) space and therefore does not include decomposition of the *n*-dimensional space into 2-D planes.

This paper proposes a new, and relatively simple, SVM algorithm for the five-phase open-end winding three-level drive supplied by two two-level five-phase inverters. The SVM algorithm is based the decomposition of three-level space vector decagon into a number of two-level decagons. A similar idea has been proposed in [17] for a three-phase NPC inverter and in [18] for a three-phase open-end winding drive. In the case of the five-phase open-end winding drive the situation is significantly more complicated since both 2-D planes have to be considered. It is shown that the proposed modulation strategy is capable of achieving the target fundamental while eliminating fully any low-order harmonic content in the output load phase voltage.

The paper begins with a review of the five-phase two-level drive characteristics followed by a general description and mathematical model of the cascaded topology, along with mapping of the space vectors into the 2-D planes. Next, the proposed modulation method is described. It is shown that due to the nature of the five-phase topology one of the inverters needs to be operated using so called multi-frequency SVM [19]. Finally, the performance of the proposed SVM scheme is verified via simulation.

## II. GENERAL PROPERTIES OF TWO-LEVEL FIVE-PHASE DRIVES

Prior to considering the SVM scheme 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 2-D sub-spaces, so-called *α-β* and *x-y* sub-spaces [20]. 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 2-D 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, as shown in Fig. 1. Space vectors are labeled with decimal numbers, which, when converted into binary code, 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, respectively, $|\overline{v}_s| = 4/5\cos(2\pi/5)V_{dc}$, $|\overline{v}_m| = 2/5V_{dc}$, and $|\overline{v}_l| = 4/5\cos(\pi/5)V_{dc}$. Four active space vectors are required to generate sinusoidal voltages [1]. In order to provide zero average voltage in the *x-y* plane two neighbouring large and two medium space vectors are selected [20]. It is shown in [20] that the maximum peak value of the output fundamental phase-to-neutral voltage in the linear modulation region is $v_{max} = 0.525V_{dc}$, resulting in the maximum modulation index, $M = 1.05$. Switching pattern is a symmetrical PWM with two commutations per inverter leg.

## II. FIVE-PHASE OPEN-END WINDING TOPOLOGY

Fig. 2 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). 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. Using the notation of Fig. 2, phase voltages of the stator winding can be given as:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \\ v_{ds} \\ v_{es} \end{bmatrix} = (1/5)\begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix}\begin{bmatrix} v_{A1N1} - v_{A2N2} \\ v_{B1N1} - v_{B2N2} \\ v_{C1N1} - v_{C2N2} \\ v_{D1N1} - v_{D2N2} \\ v_{E1N1} - v_{E2N2} \end{bmatrix} \tag{1}$$

Since a single-sided five-phase supply gives nine levels in the phase voltages, it is expected that in a five-phase dual-inverter topology 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:

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

where $\underline{a} = \exp(j2\pi/5)$. Using (1) and (2), one gets

$$\begin{aligned} \underline{v}_{\alpha-\beta} &= \underline{v}_{\alpha-\beta(A1B1C1D1E1)} - \underline{v}_{\alpha-\beta(A2B2C2D2E2)} \\ \underline{v}_{x-y} &= \underline{v}_{x-y(A1B1C1D1E1)} - \underline{v}_{x-y(A2B2C2D2E2)} \end{aligned} \tag{3}$$

since $v_{N1N2}(1 + \underline{a} + \underline{a}^2 + \underline{a}^3 + \underline{a}^4) = 0$. In (3) the two space vectors on the right-hand sides of the two equations are corresponding voltage space vectors of the two five-phase two-level VSIs, which come in three different lengths, large, medium and small: $0.32366V_{dc}$, $0.2V_{dc}$, $0.123V_{dc}$ (since $V_{dc1} = V_{dc2} = 0.5\ V_{dc}$). Voltage space vectors, produced by the 1024 possible switching states are illustrated in Fig. 3 for the $\alpha$–$\beta$ plane. There are 211 space vectors, 21 active phase voltage space vectors per 36° sector and one zero vector. Space vector mapping into the $x$-$y$ plane follows the pattern that exists for a five-phase VSI, the largest vectors of the first plane map into the smallest vectors of the second plane, and vice versa [21].

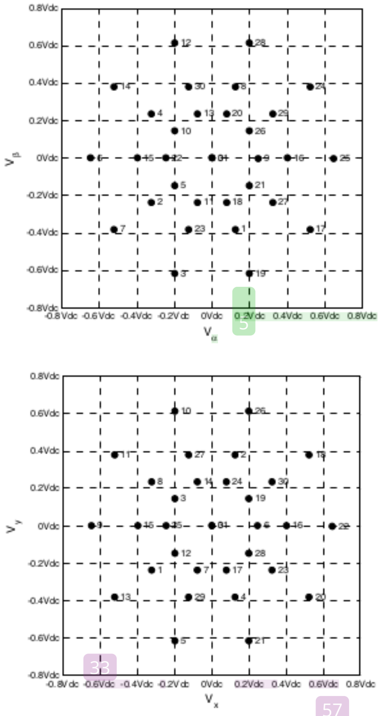

Fig. 1. Two-level five-phase VSI space vectors in the $\alpha$–$\beta$ and $x$-$y$ planes.

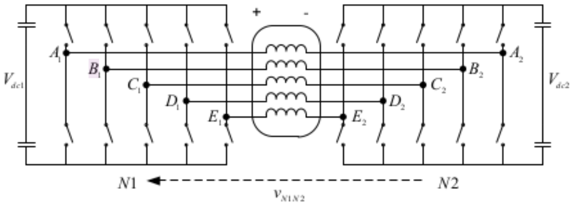

Fig. 2 Five-phase machine with dual two-level inverter supply.

## III. PRINCIPLE OF THE PROPOSED ALGORITHM

The five-phase open-end winding topology, illustrated in Fig. 2, has 1024 possible switching states. Since there are 211 space vectors, the development of a suitable SVM strategy is challenging. The complexity of selecting the proper switching states for a given command voltage can be significantly reduced if the three-level space vector decagon is decomposed into a number of two-level decagons, as illustrated in Fig 3. A similar approach was followed in [17] and [18] for the three-phase case. The centre decagon comprises vectors which can be activated if one inverter is used up to half of the achievable maximum voltage with the other one in zero state. As a consequence, the converter is in two-level mode of operation based on four active and zero vector application, as discussed in section II and [20]. As can be seen in Fig. 3, the origins of the outer decagons are located on the outer vectors of the inner decagon, denoted by the larger dots in Fig 3, which correspond to the outermost vectors and switching states given in Fig. 1. In the case of the three-phase topology [18] operation in the outer region (outer hexagon) is achieved when one inverter operates with a single voltage space vector applied (the nearest one to the reference) and the second inverter is modulated using the standard three-phase two-level SVM technique. Let the applied vector for one inverter be $\underline{v}_i$ and let the reference be $\underline{v}^*$. Here $\underline{v}_i$ is the vector produced by the inverter that is the nearest to the reference, and $\underline{v}^*$ exceeds, in magnitude, maximum voltage realisable with one inverter. The reference for the other inverter is then set as:

$$\underline{v}^{**} = -(\underline{v}^* - \underline{v}_i) \tag{4}$$

In other words, when the magnitude of the reference voltage exceeds the maximum value obtainable with one inverter, one inverter is operated in six-step (i.e., ten-step) mode while the second inverter is modulated in the standard way.

It is well known that operation of a five-phase inverter in ten-step mode without a controllable dc bus leads to uncontrollable fundamental output voltage magnitude and unwanted low order harmonics, which for the leg voltage can be expressed as a Fourier series as follows:

$$v_{leg} = \frac{1}{\pi} V_{dc} [\sin \omega t + \frac{1}{3} \sin 3\omega t + \frac{1}{5} \sin 5\omega t + \frac{1}{7} \sin 7\omega t ...] \tag{5}$$

In a five-phase system, harmonics of the order $10k\pm1$ ($k$ = 0, 1, 2, 3...) map onto the torque/flux producing subspace, $\alpha$-$\beta$, while harmonics of the order $10k\pm3$ map into the $x$-$y$ subspace. They do not produce any useful torque/flux and simply lead to large unwanted loss-producing currents. The large currents are a consequence of the relatively small impedance presented in $x$-$y$ plane. $10k\pm5$ are zero-sequence components. This leads to the requirement that the second inverter must be able to not only control the fundamental but also eliminate the unwanted low order harmonics, which are produced by applying only the large vector in $\alpha$–$\beta$ plane from one inverter. This causes unwanted harmonics in both planes since a large vector has a corresponding non-zero value in the second, $x$-$y$ plane (Fig. 1). In order to achieve this objective, the second inverter modulation scheme will need to operate in both the $\alpha$-$\beta$ and the $x$-$y$ planes, since references for the second inverter can be given as:

$$\begin{array}{ll} v_{\alpha}^{**} = -\left(v_{\alpha}^{*} - v_{i(\alpha)}\right) & v_{\beta}^{**} = -\left(v_{\beta}^{*} - v_{i(\beta)}\right) \\ v_{x}^{**} = v_{i(x)} & v_{y}^{**} = v_{i(y)} \end{array} \tag{6}$$

A space vector modulator, which achieves simultaneous control in both the $\alpha$-$\beta$ and $x$-$y$ planes, was developed in [19] in order to control multi-phase multi-motor drive systems. A schematic illustration of the SVM process is shown Fig 4. This SVM method utilises two two-level five-phase space vector modulators, as discussed previously. Each SVM operates in a separate plane. The duty cycles from the SVMs are summed according to the phase transposition rule [22]. The phase transposition [22] enables the five-phase space vector modulator to operate in either plane. This further simplifies the algorithm since the sector identification, dwell time calculation and vector look-up table are identical.

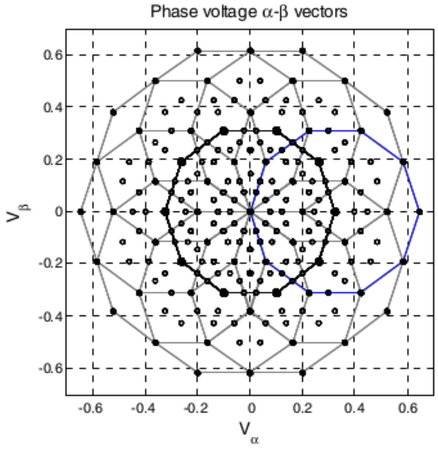

Fig. 3. Space vector distribution in the $\alpha$–$\beta$ plane.

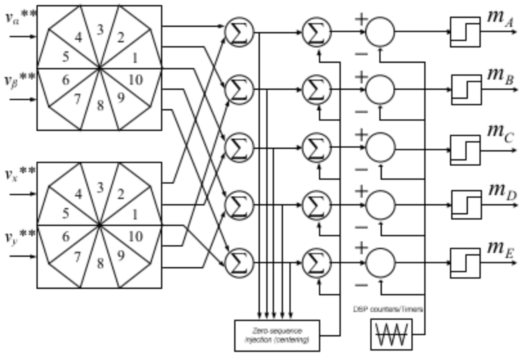

Fig. 4: Signal flow of the five-phase multi-frequency space-vector modulator.

In order to calculate the respective components of the voltages generated by the ten-step modulator, the following must be applied to the ten-step generator switching signals:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \\ v_{ds} \\ v_{es} \end{bmatrix} = \frac{V_{dc1}}{5} \begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix} \begin{bmatrix} m_A \\ m_B \\ m_C \\ m_D \\ m_E \end{bmatrix} \qquad (7)$$

where $V_{dc1}$ is the dc link voltage of the ten-step inverter (i.e. 50% of $V_{dc}$).

As a result of the proposed modulation technique for the open-end winding configuration, the converter system operates using only the large vectors from one inverter and any combination of vectors from the other inverter, as illustrated in Fig. 5. This reduces the number of switching states to 342 (320 of these are the states met when both inverters operate, while 22 states are those that are encountered when only one inverter operates). The 342 switching states produce 151 vectors in the $\alpha$-$\beta$ and $x$-$y$ planes, as shown in Fig. 6. It can be seen that no large vectors are produced in the $x$-$y$ plane. A signal flow diagram of the complete modulation scheme is presented in Fig. 7. When $M$<0.525, the switches in Fig. 7 are opened.

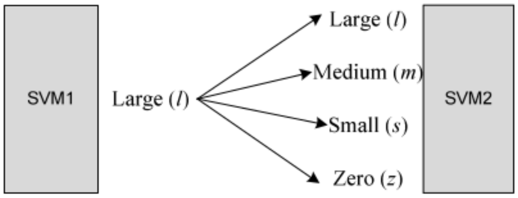

Fig. 5. Five-phase dual inverter switching combinations

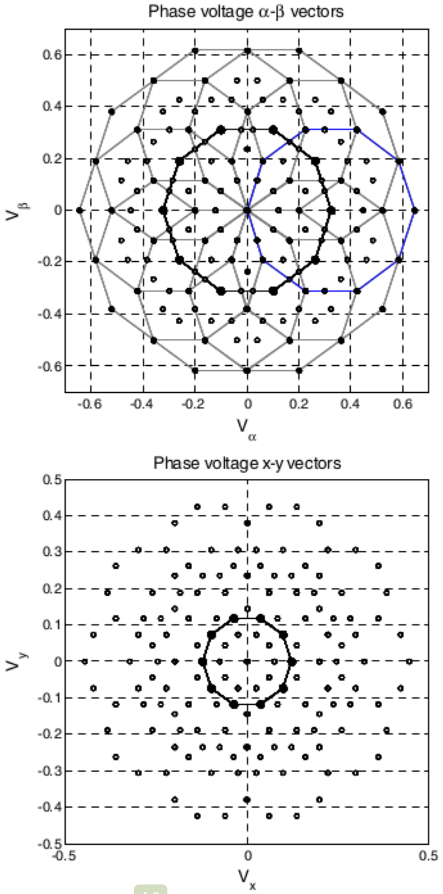

Fig. 6. Decomposed SVM space vector distribution in the $\alpha$-$\beta$ and $x$-$y$ planes.

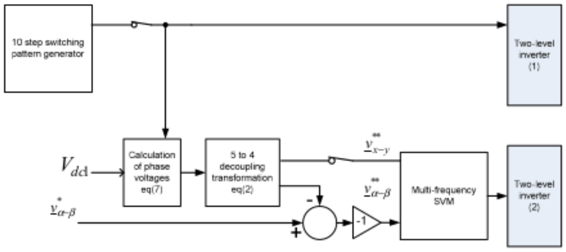

Fig. 7. Signal flow diagram of the decomposition SVM method.

## IV. SIMULATION VERIFICATION

In order to verify the converter's performance, a series of simulations were undertaken. The dc bus voltage of each inverter is 300 V ($V_{dc1} = V_{dc2} = V_{dc}/2$), output frequency is 50 Hz and switching frequency of the modulated inverter is 2 kHz. Ideal operation of the inverters is assumed, meaning that effects due to the dead-time and semiconductor volt drops were neglected. Figure 8 shows the load phase voltage waveform and its spectrum when the modulation index is 0.5, i.e. when the converter utilises only one of the inverters. It can be seen that the converter is operating in two-level mode since the output voltage comprises nine levels. There are no low order harmonics and the switching harmonics are centred around multiples of the switching frequency.

When the reference fundamental exceeds that achievable using a single inverter ($M$>0.525) the converter operates using both inverters, with one inverter in ten-step mode and the other in multi-frequency SVM mode. The most challenging operating region, as far as harmonic elimination and controlling the fundamental is concerned, occurs when modulation index is close to the modulation limits $M$=0.525 and $M$=1.05. The performance of the converter in vicinity of these two extremes is presented in Fig. 9. It can be seen that the converter is capable of achieving the target fundamental while at the same time eliminating any low-order harmonics. The number of levels seen in load phase voltage increases with modulation index, achieving the maximum of 15 levels when $M$=1.05. This is the maximum modulation index that can be achieved by the five-phase converter.

Fig. 10 shows the performance of the drive at the boundary between regions where the modulated inverter reduces the

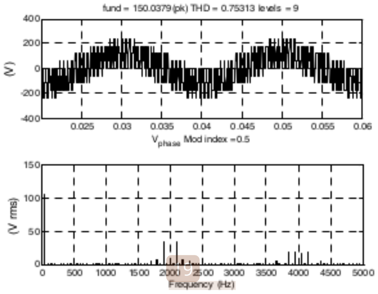

Fig. 8. Load phase voltage waveform and spectrum, $M$=0.5.

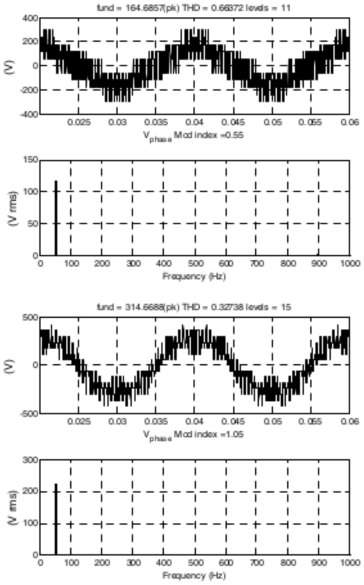

Fig. 9. Load phase voltage waveform and spectrum, $M$=0.55 and $M$ =1.05.

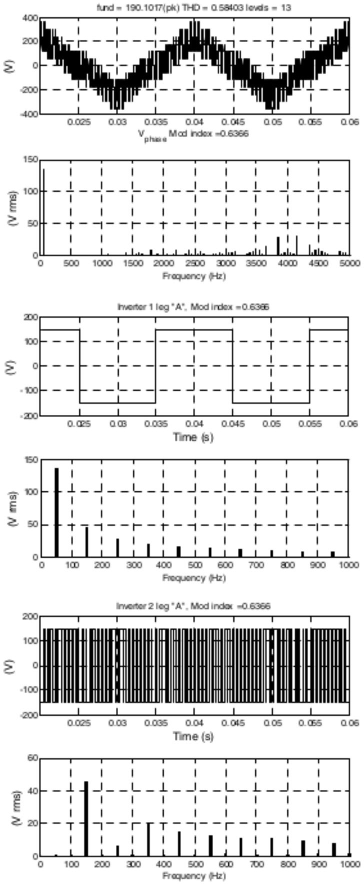

Fig. 10. Load phase voltage and inverter leg voltage waveforms and spectra, $M$=0.6366.

fundamental voltage, created by the ten-step inverter, or adds to it; this occurs when $M$ =0.6366. The converter achieves the reference fundamental with minimum low order harmonics. The leg voltages of each inverter show that the harmonics created by the ten step inverter are counter-balanced by the modulated inverter and the fundamental is overwhelmingly provided by the ten step modulator. This means that the modulated inverter is only compensating the unwanted harmonics. Finally, Fig. 11 shows the THD characteristic (calculated up to 100 kHz) of the converter for operation in the complete linear region. It is interesting to note that the achieved THD performance is better than the one obtained with a previous PWM method reported in [23].

## VI. CONCLUSION

This paper has presented a SVM method for the dual-inverter five-phase open-end winding topology, which is relatively easy to implement. When $M<0.525$ the converter operates in two-level mode utilising a single inverter. When the reference fundamental exceeds the capabilities of a single inverter ($M>0.525$), one inverter operates in ten-step mode and the other is multi-frequency space vector modulated. As a result the converter is operated in multilevel mode. The multi-frequency modulated inverter is used to control the fundamental voltage and eliminate any low order harmonics created by the ten-step mode inverter. The method has been verified by simulation. An experimental prototype is currently being commissioned and the experimental results will be reported in due course.

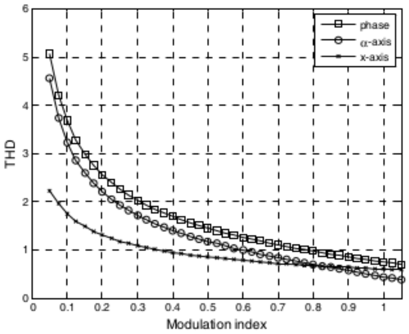

Fig. 11. Load phase voltage THD characteristic: $M$=0.025 to $M$=1.05.

## REFERENCES

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

[2] P. Lezana, J. Pou, T. A. Meynard, J. Rodriguez, S. Ceballos, and F. Richardeau, "Survey on fault operation on multilevel inverters," *IEEE Trans. on Ind. Elec.*, vol.57, no.7, 2010, pp.2207-2218.

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

[4] S. Lu, S. Mariethoz and 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, 2010, pp. 1815-1824.

[5] K. A. Corzine, S. D. Sudhoff and C. A. Whitcomb, "Performance characteristics of a cascaded two-level converter," *IEEE Trans. on Energy Conversion*, vol. 14, 1999, pp. 433-439.

[6] B. A. Welchko and J. M. Nagashima, "A comparative evaluation of motor drive topologies for low-voltage, high-power EV/HEV propulsion systems," in *IEEE Proc. Int. Symp. on Ind Elec. ISIE*, Rio de Janerio, Brazil, 2003, pp. 379-384.

[7] C. Rossi, G. Grandi, P. Corbelli and D. Casadei, "Generation system for series hybrid powertrain based on dual two-level inverter," in *Proc. Eur. Power Elec. and Appl. Conf. EPE,* Barcelona, Spain, 2009, CD-ROM.

[8] G. Grandi, C. Rossi, A. Lega and D. Casadei, "Multilevel operation of a dual two-level inverter with power balancing capability," in *Proc. IEEE Industry Applications Society Annaul Meeting IAS*, Tampa, Florida, USA, 2006, pp. 603-610.

[9] Y. Kawabata, M. Nasu, T. Nomoto, E. C. Ejiogu and 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, 2002, pp. 783-789.

[10] L. Shuai and K. Corzine, "Multilevel multi-phase propulsion drives," in *Proc. IEEE Electric Ship Technologies Symposium*, Philadelphia, PA, USA 2005, pp. 363-370.

[11] C. M. Hutson, G. K. Venayagamoorthy and K. A. Corzine, "Optimal SVM switching for a multilevel multi-phase machine using modified discrete PSO," in *Proc. IEEE Swarm Intelligence Symposium*, St. Louis, MO, CD-ROM, 2008.

[12] Q.Song, X.Zhang, F.Yu and C.Zhang, "Research on PWM techniques of five-phase three-level inverter," in *Proc. Int. Symp. on Power Elec., Electrical Drives, Automation and Motion SPEEDAM*, Taormina, Italy, 2006, pp.S23_16-S23_20.

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

[14] O. López, J. Alvarez, J. Doval-Gandoy and F. D. Freijedo, "Multilevel multiphase space vector PWM algorithm," *IEEE Trans. on Ind. Elec.*,vol. 55, no. 5, 2008, pp. 1933-1942.

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

[16] K. K. Mohapatra and 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, 2006, pp. 20-28.

[17] A. K. Gupta and A. M. Khambadkone, "A space vector PWM scheme for multilevel inverters based on two-level space vector PWM," *IEEE Trans. on Ind. Elec.*, vol. 53, 2006, pp. 1631-1639.

[18] G. Shiny and M. R. Baiju, "Space Vector PWM scheme without sector identification for an open-end winding induction motor based 3-level inverter," in *Proc. IEEE Industrial Elec. Soc. Annual Meeting IECON,* Porto, Portugal, 2009, pp. 1310-1315.

[19] D. Dujic, G. Grandi, M. Jones and E. Levi, "A space vector PWM scheme for multi-frequency output voltage generation with multiphase voltage-source inverters," *IEEE Trans. on Ind. Elec.*, vol. 55, 2008 pp. 1943-1955.

[20] D. Dujic, M. Jones and 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, 2009, pp. 1-13.

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

[22] E.Levi, M.Jones, S.N.Vukosavic and H.A.Toliyat, "A novel concept of a multiphase, multi-motor vector controlled drive system supplied from a single voltage source inverter," *IEEE Trans. on Power Elec*., vol. 19, no. 2, 2004, pp. 320-335.

[23] M. Jones, W. Satiawan and E. Levi, "A five-phase multilevel space-vector PWM algorithm for a dual-inverter supplied drive," in *Proc. IEEE Ind. Elec. Soc. Annual Meeting IECON,* Phoenix, AZ, USA, 2010, pp. 2455-2460.

# 3.A Three-level Five-phase Space-vector Modulation Algorithm Based on the Decomposition Method(IEMDC2011)

ORIGINALITY REPORT

| 20% | 11% | 17% | 2% |
|---|---|---|---|
| SIMILARITY INDEX | INTERNET SOURCES | PUBLICATIONS | STUDENT PAPERS |

PRIMARY SOURCES

| | | |
|---|---|---|
| 1 | www.deepdyve.com<br>Internet Source | 1% |
| 2 | vuir.vu.edu.au<br>Internet Source | 1% |
| 3 | Mario J. Duran, F. J. Barrero, S. L. Toral, Emil Levi. "Multi-Dimensional Space Vector Pulse Width Modulation Scheme for Five-Phase Series-Connected Two-Motor Drives", 2007 IEEE International Electric Machines & Drives Conference, 2007<br>Publication | 1% |
| 4 | Saad Khadar, Thiziri Ben Ali, Hani Benguesmia, Mekhalfia Fadhila, Abdellah Kouzou, Mohamed Monir Rezaoui. "Improved performance of Backstepping Control of an open-end stator winding Five-phase Induction Motor with the fundamental and harmonic currents", 2019 International Conference on Advanced Electrical Engineering (ICAEE), 2019<br>Publication | 1% |

| | | |
|---|---|---|
| 5 | edoc.site<br>Internet Source | 1 % |
| 6 | D. Dujic, E. Levi, M. Jones. "Harmonic losses of multi-phase PWM inverter-fed drives", 2009 IEEE Energy Conversion Congress and Exposition, 2009<br>Publication | 1 % |
| 7 | Submitted to Institute of Graduate Studies, UiTM<br>Student Paper | 1 % |
| 8 | ies.ieee-ies.org<br>Internet Source | 1 % |
| 9 | Dordevic, O., M. Jones, and E. Levi. "A Comparison of Carrier-Based and Space Vector PWM Techniques for Three-Level Five-Phase Voltage Source Inverters", IEEE Transactions on Industrial Informatics, 2012.<br>Publication | 1 % |
| 10 | M. Darijevic, M. Jones, E. Levi. "A multilevel five-phase open-end winding drive with unequal DC-link voltages", 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), 2015<br>Publication | 1 % |
| 11 | www.mdpi.com<br>Internet Source | 1 % |

| | | |
|---|---|---|
| 12 | Submitted to University of Malaya<br>Student Paper | 1 % |
| 13 | doi.org<br>Internet Source | 1 % |
| 14 | M. Darijevic, M. Jones, E. Levi. "Analysis of dead-time effects in a five-phase open-end drive with unequal DC link voltages", IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, 2013<br>Publication | 1 % |
| 15 | Casadei, Domenico, Gabriele Grandi, Alberto Lega, and Claudio Rossi. "Multilevel Operation and Input Power Balancing for a Dual Two-Level Inverter with Insulated DC Sources", IEEE Transactions on Industry Applications, 2008.<br>Publication | <1 % |
| 16 | Emil Levi, Martin Jones, Slobodan N. Vukosavic, Atif Iqbal, Hamid A. Toliyat. "Modeling, Control, and Experimental Investigation of a Five-Phase Series-Connected Two-Motor Drive With Single Inverter Supply", IEEE Transactions on Industrial Electronics, 2007<br>Publication | <1 % |
| 17 | olopez.webs.uvigo.es<br>Internet Source | <1 % |

| | | |
|---|---|---|
| 18 | unsworks.unsw.edu.au<br>Internet Source | <1 % |
| 19 | www.icrepq.com<br>Internet Source | <1 % |
| 20 | Md. Shahadath Hossain Sabbir, Md. Habibullah. "Selective Voltage Vector Based Predictive Torque Control of Five-Phase Induction Motor Drive", 2020 11th International Conference on Electrical and Computer Engineering (ICECE), 2020<br>Publication | <1 % |
| 21 | Paula Garcia-Entrambasaguas, Ivan Zoric, Ignacio Gonzalez-Prieto, Mario J. Duran, Emil Levi. "Direct Torque and Predictive Control Strategies in Nine-Phase Electric Drives Using Virtual Voltage Vectors", IEEE Transactions on Power Electronics, 2019<br>Publication | <1 % |
| 22 | Slobodan N. Vukosavic. "Independent Control of Two Five-Phase Induction Machines Connected in Parallel to a Single Inverter Supply", IECON 2006 - 32nd Annual Conference on IEEE Industrial Electronics, 11/2006<br>Publication | <1 % |
| 23 | sinta3.ristekdikti.go.id<br>Internet Source | <1 % |

| | | |
|---|---|---|
| 24 | M.R. Baiju, K.K. Mohapatra, R.S. Kanchan, K. Gopakumar. "A Dual Two-Level Inverter Scheme With Common Mode Voltage Elimination for an Induction Motor Drive", IEEE Transactions on Power Electronics, 2004<br>Publication | <1 % |
| 25 | Sk Moin Ahmed, Haitham Abu-Rub, Zainal Salarti, Marco Rivera, Omar Ellabban. "Generalized carrier based pulse width modulation technique for a three to n-phase dual matrix converter", IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, 2014<br>Publication | <1 % |
| 26 | digital-library.theiet.org<br>Internet Source | <1 % |
| 27 | Submitted to University of Newcastle upon Tyne<br>Student Paper | <1 % |
| 28 | eprints.utm.my<br>Internet Source | <1 % |
| 29 | scholar.uwindsor.ca<br>Internet Source | <1 % |
| 30 | A. C. N. Maia, C. B. Jacobina, N. B. Freitas. "Open-end multi-level six-phase machine drive system with three three-phase DC-link converters", IECON 2014 - 40th Annual | <1 % |

Conference of the IEEE Industrial Electronics Society, 2014
Publication

---

| | | |
|---|---|---|
| 31 | A. Lega. "Space Vector Modulation for Multiphase Inverters Based on a Space Partitioning Algorithm", IEEE Transactions on Industrial Electronics, 2009<br>Publication | <1 % |
| 32 | Andres Mora, Jorge Juliet, Alex Santander, Pablo Lezana. "Dead-Time and Semiconductor Voltage Drop Compensation for Cascaded H-Bridge Converters", IEEE Transactions on Industrial Electronics, 2016<br>Publication | <1 % |
| 33 | Drazen Dujic, Martin Jones, Emil Levi. "Space Vector PWM for Nine-Phase VSI with Sinusoidal Output Voltage Generation: Analysis and Implementation", IECON 2007 - 33rd Annual Conference of the IEEE Industrial Electronics Society, 2007<br>Publication | <1 % |
| 34 | Mario J. Duran, Tomas Glasberger, Drazen Dujic, Emil Levi, Zdenek Peroutka. "A Modified Sector Based Space Vector PWM Technique for Five-Phase Drives", IEEJ Transactions on Electrical and Electronic Engineering, 2009<br>Publication | <1 % |

| | | |
|---|---|---|
| 35 | Tuyen D. Nguyen, Hong-Hee Lee. "Development of a Three-to-Five-Phase Indirect Matrix Converter With Carrier-Based PWM Based on Space-Vector Modulation Analysis", IEEE Transactions on Industrial Electronics, 2016<br>Publication | <1 % |
| 36 | dehesa.unex.es<br>Internet Source | <1 % |
| 37 | jpels.org<br>Internet Source | <1 % |
| 38 | repository.um.edu.my<br>Internet Source | <1 % |
| 39 | silo.pub<br>Internet Source | <1 % |
| 40 | www.investigo.biblioteca.uvigo.es<br>Internet Source | <1 % |
| 41 | "Advances in Signal and Data Processing", Springer Science and Business Media LLC, 2021<br>Publication | <1 % |
| 42 | Bodo, N., O. Dordevic, M. Jones, and E. Levi. "A comparison of three-level single-sided and dual-inverter supply for a five-phase drive", 2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC), 2012. | <1 % |

Publication

| | | |
|---|---|---|
| 43 | Carnielutti, Fernanda, Humberto Pinheiro, and Cassiano Rech. "Generalized Carrier-Based Modulation Strategy for Cascaded Multilevel Converters Operating Under Fault Conditions", IEEE Transactions on Industrial Electronics, 2012.<br>Publication | <1 % |
| 44 | D. Dujic. "A General PWM Method for a (2n+1)-Leg Inverter Supplying n Three-Phase Machines", IEEE Transactions on Industrial Electronics, 2009<br>Publication | <1 % |
| 45 | Emil Levi. "Multi-Dimensional Approach to Multi-Phase Space Vector Pulse Width Modulation", IECON 2006 - 32nd Annual Conference on IEEE Industrial Electronics, 11/2006<br>Publication | <1 % |
| 46 | Jones, M.. "Series connected quasi-six-phase two-motor drives with independent control", Mathematics and Computers in Simulation, 20060619<br>Publication | <1 % |
| 47 | Martin Jones, Emil Levi, Drazen Dujic, Joel Prieto, Federico Barrero. "Current ripple in inverter-fed five-phase drives with space- | <1 % |

| | | |
|---|---|---|
| | vector PWM", 2010 IEEE International Symposium on Industrial Electronics, 2010<br>Publication | |
| 48 | Obrad Dordevic, Martin Jones, Emil Levi. "A Comparison of Carrier-Based and Space Vector PWM Techniques for Three-Level Five-Phase Voltage Source Inverters", IEEE Transactions on Industrial Informatics, 2013<br>Publication | <1 % |
| 49 | digibuo.uniovi.es<br>Internet Source | <1 % |
| 50 | iris.unime.it<br>Internet Source | <1 % |
| 51 | theses.ucalgary.ca<br>Internet Source | <1 % |
| 52 | www.enggjournal.com<br>Internet Source | <1 % |
| 53 | www.tesla-symp06.org<br>Internet Source | <1 % |
| 54 | Darijevic, Milan, Martin Jones, Obrad Dordevic, and Emil Levi. "Decoupled Control of a Dual-Inverter Four-Level Five-Phase Drive", IEEE Transactions on Power Electronics, 2016.<br>Publication | <1 % |

| | | |
|---|---|---|
| 55 | Gupta, Ranjan K., Krushna K. Mohapatra, Apurva Somani, and Ned Mohan. "Direct-Matrix-Converter-Based Drive for a Three-Phase Open-End-Winding AC Machine With Advanced Features", IEEE Transactions on Industrial Electronics, 2010.<br>Publication | <1 % |
| 56 | Jing Huang, Keith A. Corzine, Chris M. Hutson, Shuai Lu. "Extending voltage range and reducing torque ripple of five-phase motor drives with added voltage harmonics", 2008 Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition, 2008<br>Publication | <1 % |
| 57 | Jones, Martin, Slobodan N. Vukosavic, Drazen Dujic, and Emil Levi. "A Synchronous Current Control Scheme for Multiphase Induction Motor Drives", IEEE Transactions on Energy Conversion, 2009.<br>Publication | <1 % |
| 58 | Zarri, Luca, Matteo Marano, Marco Bonavoglia, and Domenico Casadei. "Power losses of multiphase inverters", Electrical Systems for Aircraft Railway and Ship Propulsion, 2010.<br>Publication | <1 % |
| 59 | David Solomon George, M. R. Baiju. "Decoupled random modulation technique for | <1 % |

an open-end winding induction motor based 3-level inverter", 2009 IEEE Symposium on Industrial Electronics & Applications, 2009
Publication

| | | |
|---|---|---|
| 60 | Vinoth Jayakumar, Bharatiraja Chokkalingam, Josiah Lange Munda. "A Comprehensive Review on Space Vector Modulation Techniques for Neutral Point Clamped Multi-Level Inverters", IEEE Access, 2021<br>Publication | <1 % |

| | | | |
|---|---|---|---|
| Exclude quotes | On | Exclude matches | Off |
| Exclude bibliography | On | | |

# 3.A Three-level Five-phase Space-vector Modulation Algorithm Based on the Decomposition Method(IEMDC2011)

GRADEMARK REPORT

FINAL GRADE

/0

GENERAL COMMENTS

**Instructor**

PAGE 1

💬 **Comment 1**

no comment

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6