Space Vector PWM Algorithm for Diode Clamped Multi-level Inverters using Fractal Structure

P. Satish Kumar, Ch. Lokeshwar Reddy, V. Ramu

Abstract--In this paper a space vector pulse width modulation algorithm for diode clamped multilevel inverter fed induction motor using the fractal structure has been proposed and applied for three-level and five-level inverters. In this method, fractal structure is used to represent the space vector of multilevel inverters. The switching sequence is determined without using look up tables, so the memory of the controller can be saved. The 1switching times of voltage vectors are calculated at the same manner as two-level SVPWM. It is easy to implement the triangularisation algorithm, which is used to locate the tip of the reference voltage vector. Thus, the proposed method reduces the execution time and complexity of multi-level SVPWM. This method can be extended to n-level inverter also. Based on above method, the simulation is carried out for three-level and five-level inverter fed induction motor and results are presented and analyzed. The obtained total harmonic distortions for three-level and five-level inverters are 5.70% and 3.61% respectively.

Keywords: Fractal structure, Induction motor, Multi-level inverters, Modulation index, SVPWM, THD.

I. INTRODUCTION

Multi-level inverter topology being widely used in high voltage/high power applications due to its high voltage handling and good harmonic rejection capabilities with currently available power devices [1]. The harmonic contents of the output voltage are fewer than those of two-level inverter at the same switching frequency. In addition, blocking voltage of each switching device is a half of the dc link voltage; it is easy to realize high voltage and large capacity inverter system [2]. The implementation of SVPWM involves: (i) Location of the reference vector, (ii) Determination of the nearest three voltage space vectors, (iii) Determination of the switching time duration of voltage space vectors, (iv) Choosing of an optimized switching sequence [3-8].

Several studies apply the SVPWM for multi-level inverters [5]. These works use a typical SVPWM method, which approximate the output voltage by using the nearest three output vectors.

When the reference vector changes from one region to another, it may induce an output vector abrupt change. In addition we need to calculate the switching sequences and switching time of the state at every change of reference voltage location. Thus the computational complexity is greatly increasing with increasing the number of the reference vectors and it is a main limitation of the application of this typical SVPWM [6-8].In this paper, an algorithm for the generation of space vector PWM for multilevel inverter based on fractals structure [13] has been proposed and applied for three-level and five-level inverters. In this method, the space vector representation of a higher level inverter can be conceived as generated from the space vector representation of two-level inverter, wherein the sectors of two-level inverter get progressively divided and subdivided. The basic triangle is divided into four smaller triangular regions, joined by the midpoints of the sides of the triangle. The basic structure, a triangle (sector) is transformed by further dividing itself into smaller triangles. The switching sequence is determined without using look up tables by implementing the triangularisation algorithm, the switching times of voltage vectors are calculated at the same manner as two-level SVPWM.

II. INHERENT FRACTAL STRUCTURE OF MULTILEVEL INVERTER

Fig.1 (a) explains the voltage space vectors of two-level inverter. The voltage space vector locations for a three-level inverter are shown in Fig.1 (b), where A00, A01. A02, A03, A04, A05 and A06 are same as locations of voltage space vectors of two-level inverter. Consider the region marked 1 in the case of two-level inverter, formed by the vectors located at A00, A01 and A02. In the case of three-level inverter, this region has three additional voltage space vectors as shown in Fig.1 (b). The three additional switching voltage space vectors together with switching voltage space vectors located at A00, A01, and A02 results in four sectors within (sector-I) A00,A01,A02 of three-level inverter. This process gets repeated for generation of space vectors of higher level inverters.

A. SVPWM Algorithm using the Fractal Structure

This algorithm explains the procedure to adapt the space vector pulse width modulation for multilevel inverters using the fractal structure.

1. Three phase (a,b,c) to two phase (d,q) transformation using Eq. (1) and Eq. (2)
2. Identify the sector in which the tip of the reference vector located.
3. Determine of three nearest voltage vectors.
4. Perform the triangularisation algorithm.

Manuscript received November 14, 2011

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5. Calculate and compare the cancroids of each triangle with the reference vector.
6. For the higher level implementation of fractal structure, perform triangularisation algorithm till the reference vector is nearer to centroid of respective triangle on which triangularisation is to be performed using Eq. (3) to Eq. (4).
7. Switching states are obtained using Eq. (6) to Eq. (8).
8. Switching time duration is calculated, taking the time basic two-level timings in to consideration.
9. Optimized switching sequence is calculated by a) Taking the virtual zero vectors, b) Eliminating the redundant switching states, c) Considering optimum switching where only one switching is involved as the inverter changes from one state to another.

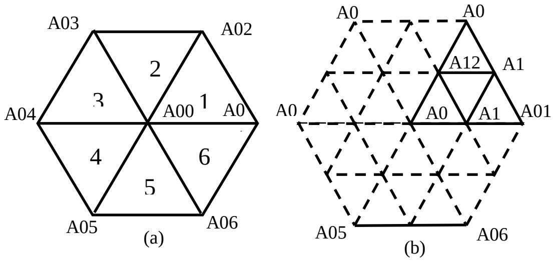

Fig. 1 Voltage space vectors of two-level and three-level inverters.

B. Three phase (a, b, c) to two phase (d, q) transformation

The three phase quantities can be transformed to their equivalent two phase quantity either in synchronously rotating frame (or) stationary frame. From this two-phase component the reference vector magnitude can be found and used for modulating the inverter output. The three phase sinusoidal voltage components are

$$V_a = V_m \sin \omega t$$
$$V_b = V_m \sin\left(\omega t - \frac{2\pi}{3}\right)$$
$$V_c = V_m \sin\left(\omega t + \frac{2\pi}{3}\right) \quad (1)$$

The magnitude and angle of the rotating vector can be found by means of Clark’s Transformation. Then, the (d, q) co-ordinates of the corresponding space vector can be obtained as

$$V_d = \frac{3}{2}(V_a)$$
$$V_q = \frac{3}{2}(V_b - V_c) \quad (2)$$

C. Location of the reference voltage vector

The identification of sector in which the tip of reference vector lies can be done using coordinate transformation of the reference vector into a two dimensional co-ordinate system. The sector can also be determined resolving the reference phase vector along a, b and c axes and repeated comparison with discrete phase voltages.

After identifying the sector, the voltage vectors at the vertices of the sector are to be determined. This can be done by the comparison of reference angle with sector angle; Fig.2 depicts SVPWM with six sectors in (d, q) reference frame with ‘α’ as the reference angle and the nearest three voltage vectors of the reference vector are the vertices of the sector.

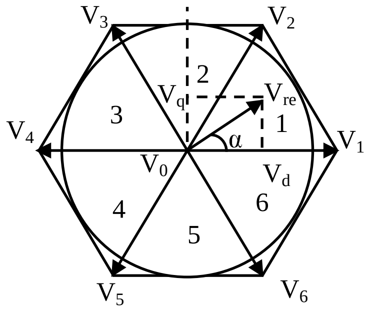

Fig. 2 Reference voltage vector location.

D. Triangularisation algorithm

The voltage space vector representation of two-level inverter grows to that of higher level inverters by repeated division of each sector due to the fractal structure. At every stage, the triangular region is divided into four smaller triangular regions, due to the presence of the additional voltage vectors. The three additional voltage vectors are located at the midpoint of each side of sector. The sectors of higher level inverter can be generated by such a repeated triangularisation.

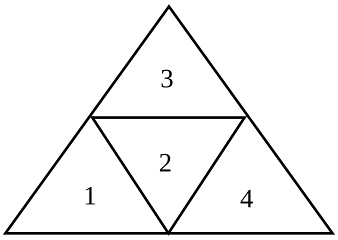

Fig. 3 Triangularisation of two-level inverter in sector-I.

The following steps are involved to perform the triangularisation:
1. Determine the sector on which triangularisation is to be performed.
2. Determine the midpoints of each side of the sector by Eq. (3) to Eq. (5). These are the co-ordinates of the three new vectors which will divide the sector into four smaller, but similar triangular regions.
3. Determine the inverter states corresponding to these vectors using Eq. (6) to Eq (8).

For example, consider region I of the two-level inverter formed by vertices A_{00}, A_{01} and A_{02}. The co-ordinates of three vertices are (α_{00},β_{00}), (α_{01},β_{01}) (α_{02},β_{02}) respectively. The co-ordinates of the three new voltage space vectors located at A_{1l}, A_{12} and A_{13} as shown in Fig.4 can be obtained from the co-ordinates of A_{00}, $A_{01}$and A_{02}.

Co-ordinates of A_{11} are

$$\alpha_{11} = \frac{1}{2}(\alpha_{00} + \alpha_{01})$$
$$\beta_{11} = \frac{1}{2}(\beta_{00} + \beta_{01}) \quad (3)$$

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Co-ordinates of A_{12} are

$$\alpha_{12} = \frac{1}{2}(\alpha_{00} + \alpha_{02})$$

$$\beta_{12} = \frac{1}{2}(\beta_{00} + \beta_{02}) \qquad (4)$$

Co-ordinates of A_{13} are

$$\alpha_{13} = \frac{1}{2}(\alpha_{01} + \alpha_{02})$$

$$\beta_{13} = \frac{1}{2}(\beta_{01} + \beta_{02}) \qquad (5)$$

The associated switching vector states can also be determined in a similar manner. The inverter switching states correspond to the voltage space vector located at A_{00}, A_{01} and A_{02} are (a_0 b_0 c_0), (a_1 b_1 c_1) and (a_2 b_2 c_2) respectively. The switching states of the new voltage space vectors at A_{11} (a_3 b_3 c_3), A_{12} (a_4 b_4 c_4) and A_{13} (a_5 b_5 c_5) can be obtained as

$$X_3 = \frac{1}{2}(X_0 + X_1) \qquad (6)$$

$$X_4 = \frac{1}{2}(X_0 + X_2) \qquad (7)$$

$$X_5 = \frac{1}{2}(X_2 + X_1) \qquad (8)$$

Where 'X' takes a, b and c for the respective phases.

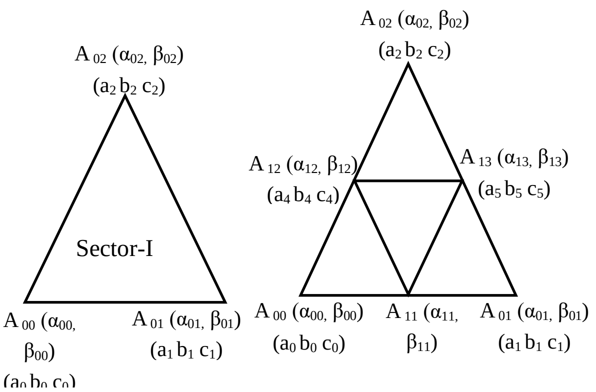

Fig. 4 First triangularisation of two-level inverter.

The Eq. (3) to Eq. (5) represents the arithmetic procedure used in the proposed method for dividing a triangular region (sector) into four similar regions, by generating three additional vectors situated at the mid points of the sides forming the original triangular region. This is referred the triangularisation algorithm. In order to generate sectors of higher level inverter by progressively dividing sectors of two-level inverter, the triangularisation algorithm is repeatedly applied. In the fractal theory, algorithms whose repeated iterations will result in the pattern to grow or evolve, are referred an iterated function system, the repeated iteration of triangularisation algorithm will grow the inherent fractal structure in space vector representation of multilevel inverters. Therefore, the triangularisation algorithm can be viewed as the iterated function system for this fractal structure.

E. Comparison of reference vector with the centroid

The location of the tip of the reference voltage space vector from among these four triangular regions is found by determining the region whose centroid is the closest to the tip of reference space vector. The co-ordinates of the centroid of an equilateral triangle can be determined as the average of co-ordinates of the three vertices. For an equilateral triangle with the co-ordinates of the vertices as (α_1, β_1), (α_2, β_2), (α_3, β_3), co-ordinates of the centroid (α_{cent}, β_{cent}) are given by

$$\alpha_{cent} = \frac{1}{3}(\alpha_1 + \alpha_2 + \alpha_3)$$

$$\beta_{cent} = \frac{1}{3}(\beta_1 + \beta_2 + \beta_3) \qquad (9)$$

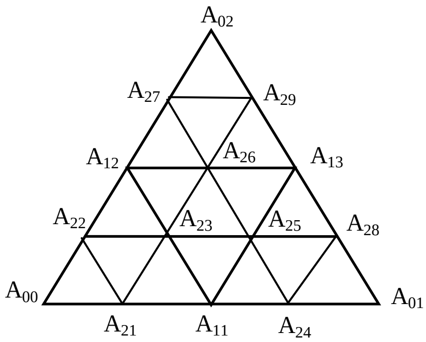

Fig. 5 Triangularisation of sector-I of equivalent five-level inverter.

The triangle with centroid closest to tip of reference space vector is $\Delta A_{11}A_{12}A_{13}$. The triangularisation algorithm has to be applied once again in case of five-level inverter. The application of Eq. (3) to Eq. (5) to $\Delta A_{11}A_{12}A_{13}$ will generate further three new voltage space vectors A_{23}, A_{25}, A_{26} and also the inverter states corresponding to these new voltage vectors. Thus, the three-level inverter space vector diagram is further divided into four smaller triangles for a five-level inverter space vector diagram as shown in Fig.5. From these four triangles, one triangle enclosing the reference space vector is chosen such that its centroid is the closest to tip of reference space vector. The sector is identified and the inverter states corresponding to the switching vectors located at the vertices of the identified sector are also generated simultaneously.

F. Calculation of switching times

The switching time durations are calculated, taking the basic two-level timings into consideration, as these can be extended to N- level. The determination of the duration of operation of the switching voltage space vectors is simplified by mapping the sector that is identified to enclose the reference space vector to a sector of two-level inverter. The switching time durations of the vectors can be determined using the following equations.

$$T_1 = \frac{(m \times \sin(60^O - \alpha))}{\sin(60^O)} \qquad (10)$$

$$T_2 = \frac{(m \times \sin(60^O))}{\sin(60^O)} \qquad (11)$$

$$T_0 = T_S - T_1 - T_2 \qquad (12)$$

Where

$$m = \frac{V_{sr}}{\left(\frac{2}{3}\right)V_{dc}}$$

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III. IMPLEMENTATION OF SVPWM ALGORITHM FOR FIVE-LEVEL INVERTER

This section explains the proposed method for generation of SVPWM for five-level inverter fed induction motor using the fractal structure associated with the switching space vector representation of multilevel inverter.

A. Determination of switching vectors

In the case of five-level inverter, the voltage V_{dc} in the normalized space vector representation is represented by a vector of length 4. The switching vectors located at the six vertices of the hexagon forming the periphery are same as the vectors of equivalent two-level inverter, but they have the switching states as (400), (440), (040), (044), (004), (404).The position of reference space vector $A_{00}P$ for five-level inverter is as shown in Fig.6.

The first step in the proposed sector identification of this method is to determine the location of the tip of the reference space vector $A_{00}P$ from among the six regions of the equivalent two-level inverter. The region I is formed by the vertices A_{00}, A_{01} and A_{02}. The co-ordinates of the vertices are (0,0), (4,0) and (2, 2√3) respectively as shown in Fig.8. The switching states of the vector located at A_{00}, A_{01} and A_{02} are (000, 111, 222, 333, 444), (400) and (440) respectively. The next step is to divide region I into four smaller triangular regions by applying the triangularisation algorithm and generates the co-ordinates of the new voltage space vectors and the inverter states corresponding to these new switching vectors. The three new voltage space vectors divide region I into four smaller triangular regions marked as R_1, R_2, R_3 and R_4 as shown in Fig.8.

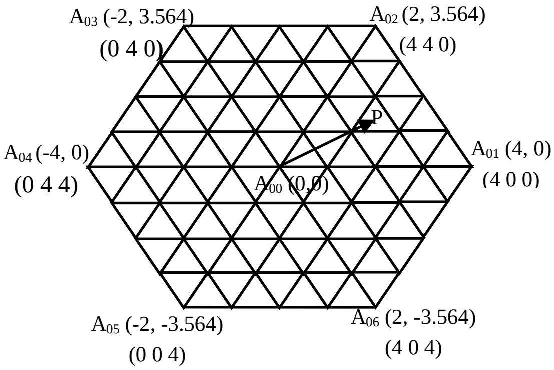

Fig. 6 Space vector representation of five-level inverter.

B. Determination of centroids

The location of the tip of the reference voltage space vector $A_{00}P$ among these four triangular regions is found by determining the region whose centroid is the closest to the tip of reference space vector. The co-ordinates of the centroid of an equilateral triangle can be determined the average of co-ordinates of the three vertices.

The triangle with centroid closest to tip of reference space vector is $\Delta A_{11}A_{12}A_{13}$. For five-level inverter the triangularisation algorithm has to be applied once again, which generates further three new voltage space vectors and also the inverter states corresponding to these new voltage vectors, thus dividing it into four smaller triangles, the triangle enclosing the reference space vector $A_{00}P$ is $\Delta A_{23}A_{25}A_{26}$ as its centroid is the closest to tip of reference space vector. The $\Delta A_{23}A_{25}A_{26}$ corresponds to sector 27 of five-level inverter. The sector is identified and the inverter states are also generated simultaneously. The switching states of five-level inverter are shown in Fig.7.

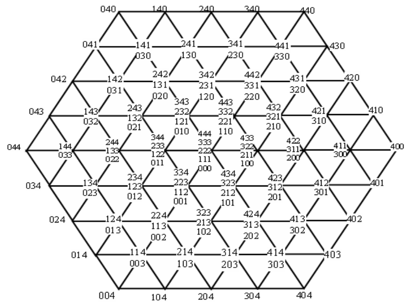

Fig. 7 Switching states of five-level inverter.

C. Determination of switching times

For the voltage reference vectorA_{00P}, the sector identified is sector 27. The voltage space vector with tip located at A_{23} becomes the virtual zero vector for sector 27. The sector 27, thus, gets mapped to sector-I of the five-level inverter. The determination of duration now reduces to that of a two-level inverter since after mapping one of the vectors of the identified sector coincides with the zero vectors. The durations of the vectors can be determined using the conventional two-level inverter.

D. Determination of optimized switching sequence

The tip of the reference vector $A_{00}P$ is located in sector 27 as shown in Fig.8. The switching states corresponding to the switching vectors at the vertices of sector 27 with redundancies are A_{23} (210, 321, 432), A_{25} (310, 421) and A_{26} (320, 431). For sector 27, the virtual zero vector at A_{23} has three redundant switching states while the voltage vectors at A_{25} and A_{26} has two redundancies each.

In the present work, if the redundancy of the virtual zero vectors are greater than two, the last two redundant switching states are selected for the virtual zero vectors. For the other two vectors, if redundant states are more than one, the last redundant state is selected. This strategy of choosing the last two redundant states for the virtual zero vectors and the last redundant state for the other vectors will achieve optimum switching sequence.

TABLE I

Switching states in sector-I

Samples	States	Switching sequence
1	66-102-103-67	300-400-410-411
2	67-103-69-66	411-410-310-300
3	68-103-67-69	310-410-411-421
4	69-104-103-68	421-420-410-310
5	68-103-104-69	310-410-420-421
6	71-69-104-70	431-421-420-320
7	70-104-105-71	320-420-430-431

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8	71-105-73-70	431-430-330-320
9	72-105-71-73	330-430-431-441
10	73-106-105-72	441-440-430-330
11	72-105-106-73	330-430-440-441
12	73-106-105-72	441-440-430-330

The selection will result in switching states 321-432 for the virtual zero vectors. The other vectors have switching states 421 and 431. With these states, switching sequence of inverter for the sector number 27 is 321-421-431-432 during a sampling interval and 432-431-421-321 for the subsequent sampling interval. It may be noted that only one switching occurs as the inverter changes state. By following the above procedure of the fractal approach for five-level inverter, the switching states and switching sequence of a reference vector is generated. The optimum switching pattern for the twelve samples in sector-I of five-level inverter is shown in the Table I.

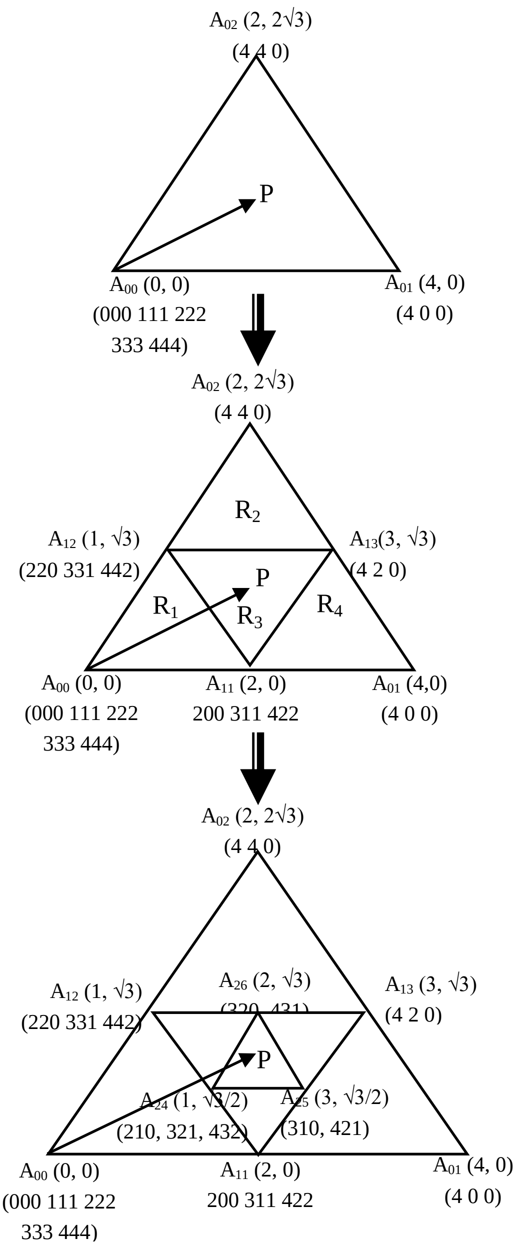

Fig. 8 Sector identification and switching vector determenation of five-level inverter.

IV. RESULTS AND DISCUSSIONS

To validate the proposed method of the generation of space vector pulse width modulation for multilevel inverters using the fractal structure, simulation studies have been carried out with a dc link voltage of 400V and modulation index of 0.8.

Fig.9 to Fig.13 shows the simulation results for three-level inverter. Fig.9 shows the process of triangularisation and rotation of reference voltage vector through 0° to 360° of three-level inverter. Fig.10 shows the line voltages of three-level inverter. The rotor speed and torque response of three-level inverter fed induction motor are shown in Fig.11 and Fig.12. The harmonic spectrum of inverter output voltage along with THD is shown in Fig.13.

Fig.14 to Fig.18 shows the simulation results for five-level inverter. Fig.14 shows the process of triangularisation and rotation of reference voltage vector through 0° to 360° of five-level inverter. Fig.15 shows the line voltages of five-level inverter. The rotor speed and torque response of five-level inverter fed induction motor are shown in Fig.16 and Fig.17. The harmonic spectrum of five-level inverter output voltage along with THD is shown in Fig.18. The performance of three-level and five-level inverters with the proposed algorithm is compared in Table-II.

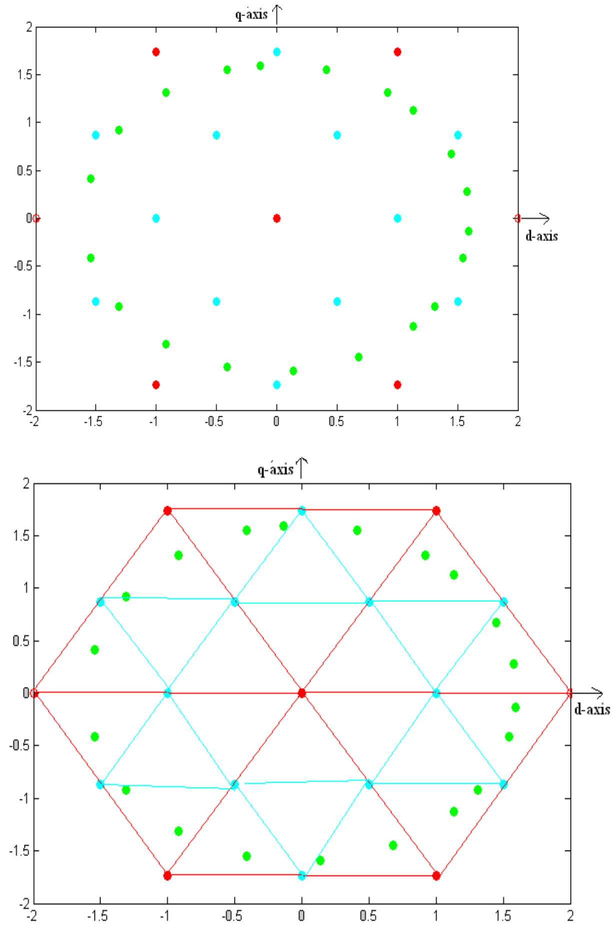

Fig. 9 Space vector diagram of three-level inverter when reference angle ‘α’ rotated for 360°.

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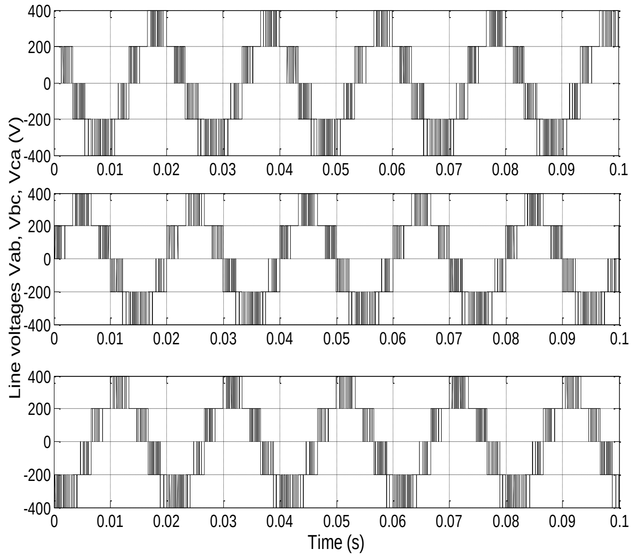


Fig. 10 Line-to-line voltages of three-level inverter.

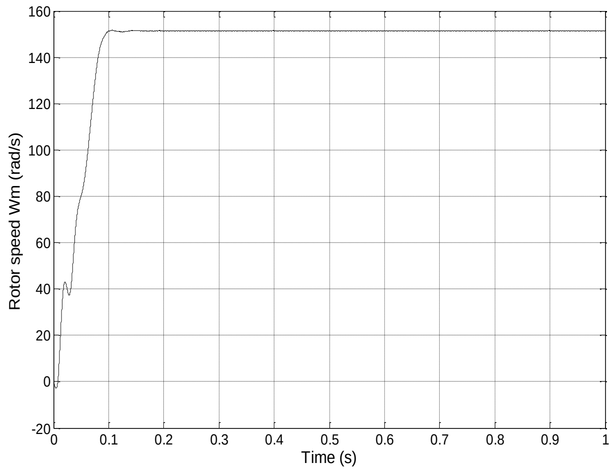


Fig. 11 Speed response of three-level inverter fed induction motor.

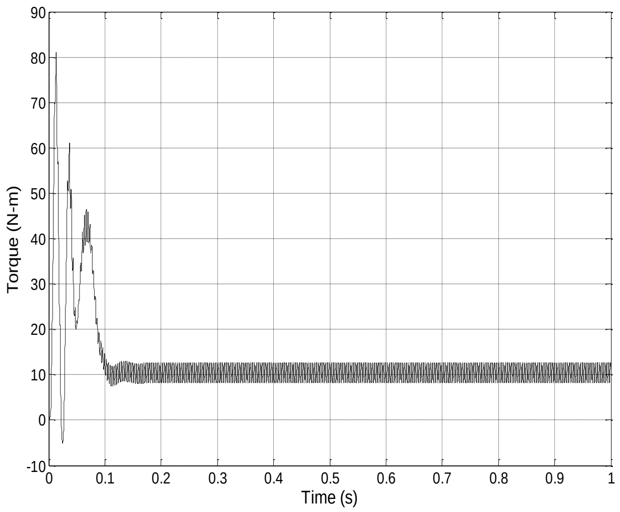


Fig. 12 Torque response of three-level inverter fed induction motor.

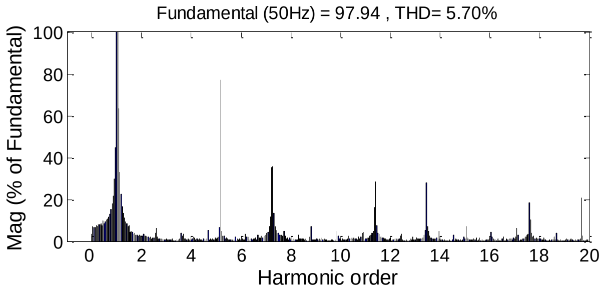
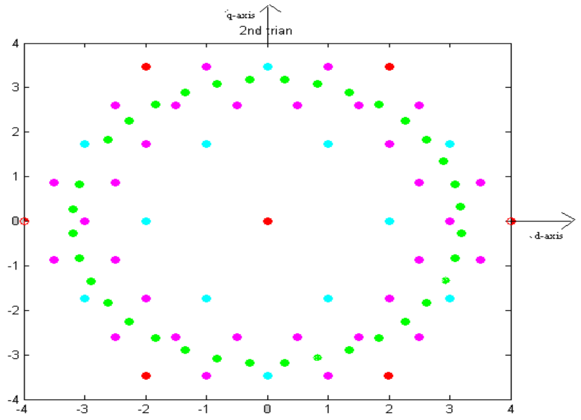


Fig. 13 Output voltage harmonic spectrum of three-level inverter.



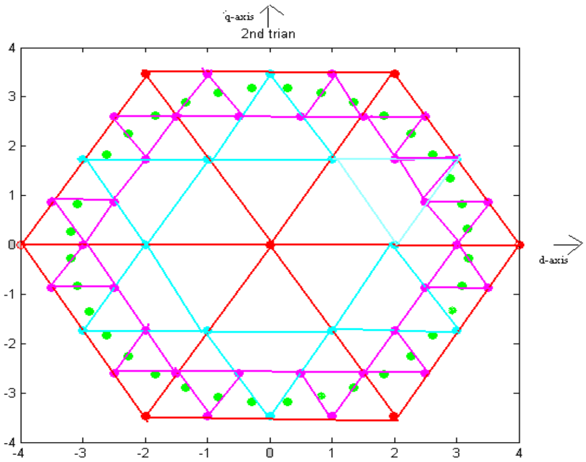


Fig. 14 Space vector diagram of five-level inverter when reference angle (α) rotated through 360°.

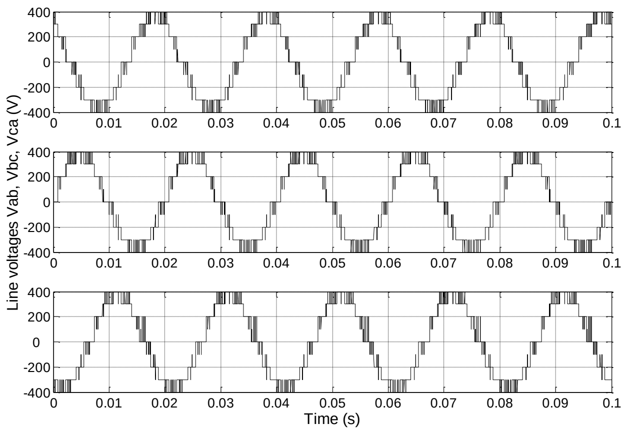


Fig.15 Line-to-line voltages of five-level inverter.

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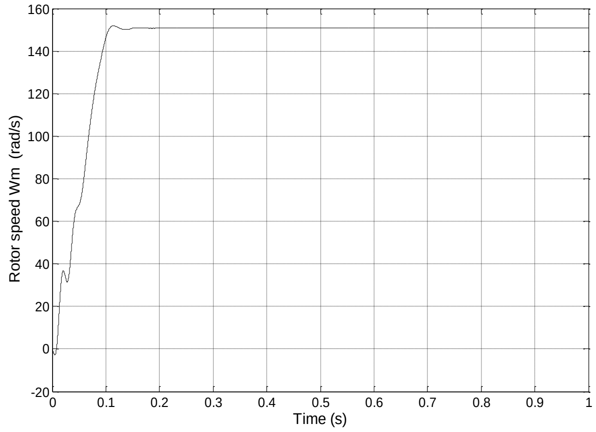

Fig. 16 Speed response of induction motor.

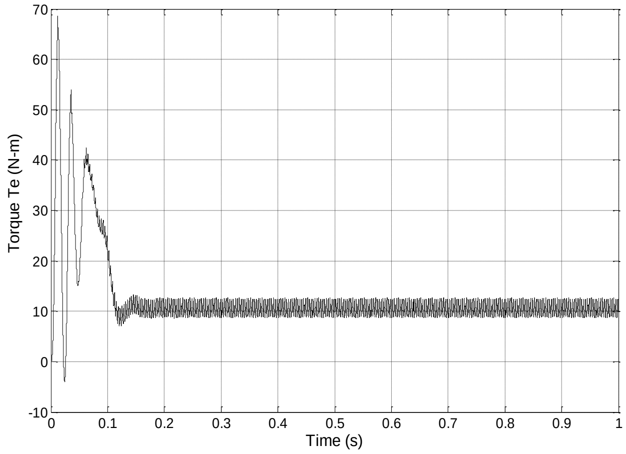

Fig. 17 Torque response of five-level inverter fed induction motor

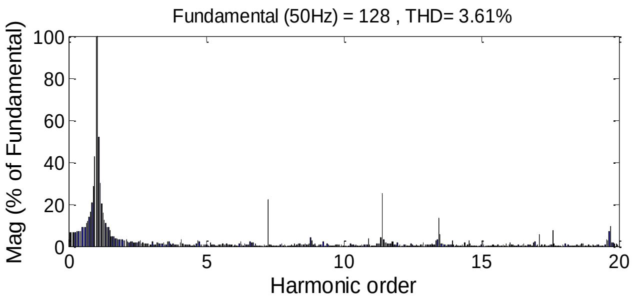

Fig. 18 Output voltage harmonic spectrum of five-level inverter.

TABLE II

Performance of the Inverters

S.No.	Parameters	Three-level Inverter	Five-level Inverter
1	Torque (N-m)	10.41	10.67
2	Speed (rad/s)	151.4	150.71
3	I_{rms} (A)	5.129	4.859
4	THD (%)	5.70	3.61

V. CONCLUSIONS

In the field of high power, high performance applications the multilevel inverters seem to be the most promising alternative. In this paper, an algorithm for the generation of space vector PWM for multilevel inverter based on fractals structure has been proposed and applied for three-level and five-level inverters. In this method, the switching sequence is determined without using look up tables by implementing the triangularisation algorithm, the switching times of voltage vectors are calculated at the same manner as two-level SVPWM. It can also be applied to the SVPWM method for n-level. From the results it has shown that the five-level inverter attains a steady state response faster than that of three-level inverter and the torque ripple and THD is reduced. The obtained total harmonic distortions for three-level and five-level inverters are 5.70% and 3.61% respectively. Thus the complexity and execution time of three-level and five-level SVPWM have been reduced by using this algorithm.

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