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SPACE VECTOR PWM SIGNAL GENERATION FOR ANY MULTILEVEL INVERTER BY USING REVERSE MAPPING TECHNIQUE

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Abstract—This paper proposes a generalized method for the generation of space vector pulse width modulation (SVPWM) signals for multilevel inverters. In the proposed method, the actual sector containing the tip of the reference space vector need not be identified. A method is presented to identify the center of a sub hexagon containing the reference space vector. Using the center of the sub hexagon, the reference space vector is mapped to the innermost sub hexagon, and the switching sequence corresponding to a two-level inverter is determined. A new technique is proposed in this paper, by which these two-level vectors are translated to the switching vectors of the multilevel inverter by adding the center of the sub hexagon to the two-level vectors. The proposed method can be extended to any n -level inverter, and a generalized algorithm is proposed. The scheme is explained for a five-level inverter, and experimental results are presented for a three-level inverter and seven-level inverter.

Index Terms—multilevel inverter, reverse mapping, space vector pulse width modulation (SVPWM).

I. INTRODUCTION

IN THE FIELD of medium- and high-power applications, multilevel inverters have emerged as an attractive choice [1]–[3]. The output waveforms of the multilevel inverters are smoother than those of a two-level inverter as the output voltage is synthesized from multiple levels of dc voltage. The most widely used techniques for implementing the pulse width modulation (PWM) strategy for multilevel inverters are sine-triangle PWM (SPWM) and space vector PWM (SVPWM) [4]–[24]. In multilevel SPWM, the reference sine wave is compared with a number of level-shifted carriers to decide the switches to be turned on [5]. In the SVPWM scheme, the sampled value of the reference voltage space vector which is the combined effect of the three-phase voltages is realized by switching the nearest voltage space vectors among the inverter voltage vectors [6]. There are different techniques available for implementing SVPWM for multilevel inverters [7]–[24]. In general, the SVPWM implementation involves the sector identification, switching-time calculation, switching-vector determination, and optimum-switching-sequence selection for the inverter voltage vectors [7]–[20], [23].

The sector identification can be done by coordinate transformation [8], [9], [16] or by repeated comparison of the three phase reference voltages [7], [15]. The lookup tables can be used for determining the switching vectors in optimum switching sequence [6]–[20]. The calculation of the duration of the switching vectors can be simplified using the mapping technique, in which the identified sector of the multilevel inverter is mapped to a corresponding

sector of the two-level inverter [13]–[15], [23].

The SVPWM methods using the principle of equivalence with SPWM can generate the SVPWM signals directly from the instantaneous reference phase voltages for multilevel inverters without using lookup tables [21], [22]. The fractal-based approach for SVPWM generation using a triangularization scheme to generate the voltage space vectors also does not require lookup tables [23].

This paper proposes a new approach to generate SVPWM signals for multilevel inverters. The proposed method uses sector identification only at the two-level. In the proposed method, the actual sector (where the tip of the instantaneous reference space vector lies) in the space vector diagram of a multilevel inverter is not required to be identified. A method using the principle of mapping is proposed for generating the switching vectors corresponding to the actual sector and the optimum switching sequence of a multilevel inverter from that of the two-level inverter. An algorithm is proposed for generating SVPWM for any n -level inverter. The proposed method can be used for an inverter with an even number of levels also. The scheme is explained with a five-level inverter, and experimental results for a three-level inverter are presented.

II. PRINCIPLE OF THE PROPOSED METHOD

Fig. 1 shows the space vector diagram of a five-level inverter. The redundant vectors are not shown for simplicity. The small triangles formed by the adjacent voltage space vectors are called sectors. Such six sectors around a voltage space vector forms a hexagon called sub hexagon [14], [15]. The space

vector diagram of a multilevel inverter can be viewed as composed of a number of such subhexagons. The shaded regions in Fig. 1 show two subhexagons. They are represented as “subhexagon I” (referred as inner subhexagon) having the vector 000 as the center and “subhexagon II” having the vector 330 as the center. The inner subhexagon can be viewed as a space vector diagram of a two-level inverter whose inverter voltage vectors switch between the lowermost levels. Subhexagon II can be also viewed as a space vector diagram of a two-level inverter,

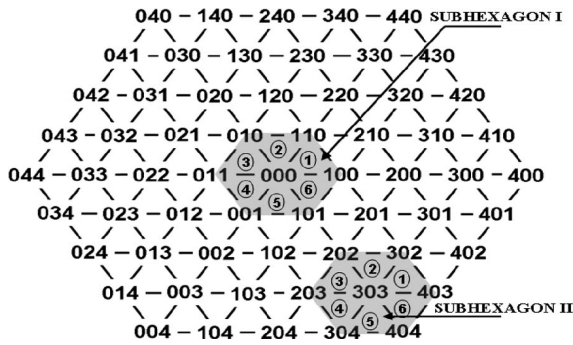


Fig. 1. Space vector diagram of a five-level

whose voltage vectors involve higher levels. The shifting of the subhexagons in the space vector diagram of a multilevel inverter to the zero vector 000 simplifies the switching time calculations associated with multilevel inverters [13]–[15], [23]. The shifting of subhexagon II in the space vector diagram of a multilevel inverter toward the zero vector 000 involves the mapping of the sectors of subhexagon II to the sectors of the inner subhexagon. This is done by subtracting the vector at the center of subhexagon II from its other vectors. In a reverse approach of mapping, the inner subhexagon can be mapped to subhexagon II by adding the voltage space vector at the center of subhexagon II to the vectors of the inner subhexagon. Consider the voltage space vectors 000, 001, 101, and 111 associated with sector 5 of the inner subhexagon and the voltage space vector 303 which is the vector at the center of subhexagon II. Adding the voltage space vector 303 to the voltage space vectors associated with sector 5 of the inner subhexagon gives the vectors 303 (000 + 303), 304 (001 + 303), 404 (101 + 303), and 414 (111 + 303) which are the vectors associated with sector 5 of subhexagon II. Similarly, the voltage space vectors associated with any subhexagon can be generated by adding the vector at the center of the particular subhexagon to the voltage space vectors of the corresponding sectors in the inner subhexagon. In this paper, the mapping of the inner subhexagon to any other outer subhexagon (referred as *reverse mapping*) is used to generate the vectors associated with any sector in the space vector diagram of the multilevel inverter.

Fig. 2 shows the instantaneous reference space

vector OT . The tip of the reference space vector OT lies in sector 1 of subhexagon III. The vector 330 is the center of subhexagon III which contains the tip of the reference space vector. By subtracting this vector at the center of the sub-hexagon, the reference space vector can be mapped as OT^* into sector 1 of the inner subhexagon. The vectors 000, 100, and 110 are associated with sector 1 of the inner subhexagon. By adding these vectors with the vector located at the center of subhexagon III, the actual switching vectors 330, 430, and 440 for the reference space vector can be generated. Therefore, the actual sector that contains the reference space vector need not to be identified for determining vectors to be switched by the inverter to realize the reference space vector.

In the proposed scheme, the vector at the center of the sub-hexagon is to be determined for the mapping of the reference whose voltage vectors involve higher levels. The shifting of the subhexagons in the space vector diagram of a multilevel inverter to the zero vector 000 simplifies the switching time calculations associated with multilevel inverters [13]–[15], [23]. The shifting of subhexagon II in the space vector diagram of a multilevel inverter toward the zero vector 000 involves the mapping of the sectors of subhexagon II to the sectors of the inner subhexagon. This is done by subtracting the vector at the center of subhexagon II from its other vectors.

In a reverse approach of mapping, the inner subhexagon can be mapped to subhexagon II by adding the voltage space vector at the center of subhexagon II to the vectors of the inner subhexagon. Consider the voltage space vectors 000, 001, 101, and 111 associated with sector 5 of the inner subhexagon and the voltage space vector 303 which is the vector at the center of subhexagon II. Adding the voltage space vector 303 to the voltage space vectors associated with sector 5 of the inner subhexagon gives the vectors 303 (000 + 303), 304 (001 + 303), 404 (101 + 303), and 414 (111 + 303) which are the vectors associated with sector 5 of subhexagon II. Similarly, the voltage space vectors associated with any subhexagon can be generated by adding the vector at the center of the particular subhexagon to the voltage space vectors of the corresponding sectors in the inner subhexagon. In this paper, the mapping of the inner subhexagon to any other outer subhexagon (referred as *reverse mapping*) is used to generate the vectors associated with any sector in the space vector diagram of the multilevel inverter.

Fig. 2 shows the instantaneous reference space vector OT . The tip of the reference space vector OT lies in sector 1 of subhexagon III. The vector 330 is the center of subhexagon III which contains the tip of the reference space vector. By subtracting this vector at the center of the sub-hexagon, the reference space vector can be mapped as OT^* into sector 1 of the inner subhexagon. The vectors 000, 100, and 110 are associated with sector 1 of the inner subhexagon. By

adding these vectors with the vector located at the center of subhexagon III, the actual switching vectors 330, 430, and 440 for the reference space vector can be generated. Therefore, the actual sector that contains the reference space vector need not to be identified for determining vectors to be switched by the inverter to realize the reference space vector.

In the proposed scheme, the vector at the center of the sub-hexagon is to be determined for the mapping of the reference

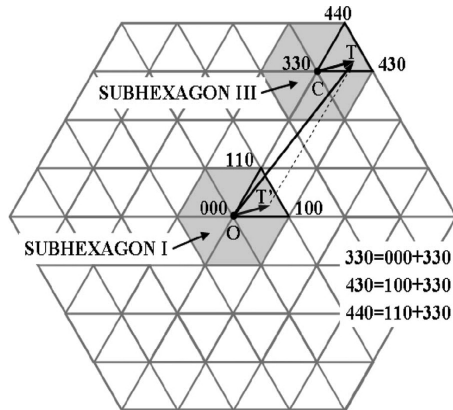


Fig. 2. Generating switching vectors through reverse mapping.

space vector to the inner subhexagon and for switching vector generation. A new approach is proposed to identify the center of the subhexagon by generating candidate voltage space vectors for the center of the subhexagon.

This vector at the center of the subhexagon is used to map the reference space vector to the inner subhexagon. Once the reference space vector is mapped to the inner subhexagon, the situation is that of generating the switching vectors and the sequence for a two-level inverter [13]–[15], [23]. The switching vector and the sequence of the inner subhexagon can be translated to the switching vector and sequence of the multilevel inverter by the proposed principle of reverse mapping. The principle of the proposed method in this paper can be summarized as follows:

- 1) identification of the center of the subhexagon that contains the tip of the reference space vector;
- 2) mapping of the reference space vector to a sector of the inner subhexagon;
- 3) determination of the duration of switching vectors and optimum switching sequence using a two-level algorithm;
- 4) generation of the actual switching vectors for the mul-tillevel inverter by adding the vector at the center of the subhexagon to the vectors obtained in 3).]

III. IDENTIFYING THE CENTER OF SUBHEXAGON

The space vector diagram of a five-level inverter, shown in Fig. 3, can be viewed as formed of four layers. These are the innermost layer (layer 1), the layer outside of layer 1 (layer 2), the next outer layer (layer 3), and the outermost layer (layer 4). These layers are represented as L_1 , L_2 , L_3 , and L_4 in Fig. 3, and the instantaneous reference space vector OT is in layer 4 (L_4). Layer 1 is the same as the inner subhexagon mentioned in section II. Fig. 3 also shows the six 60° regions S_1 , S_2 , S_3 , S_4 , S_5 , and S_6 . The subhexagon associated with the instantaneous reference space vector can be considered as centered on the inner side of layer 4. Among the vectors on the inner side of the layer, the vectors which belong to the 60° region S_3 are the most suitable vectors (*candidate vectors*) for the center of the sub-hexagon since this region contains the reference space vector. In this paper, these candidate vectors are automatically generated from the vectors of the inner subhexagon, and the candidate

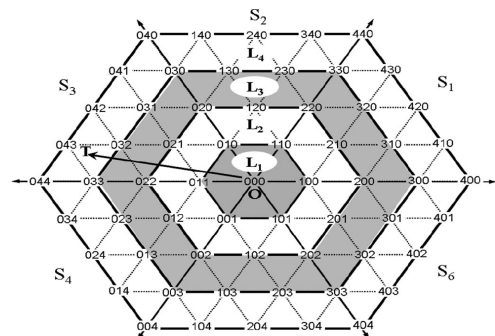


Fig. 3. Layers in the space vector diagram of a five-level inverter.

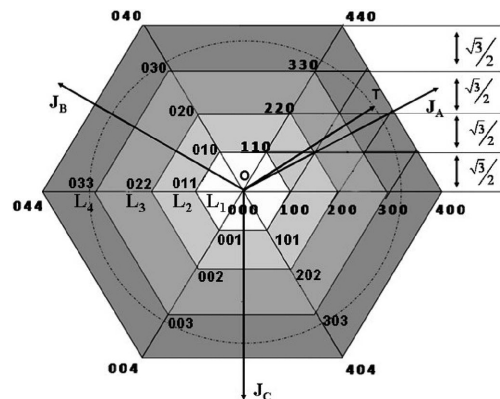


Fig. 4. j_a , j_b , and j_c axes and width of each layer for a five-level inverter

vector which is closest to the tip of the reference space vector is chosen as the center of the subhexagon. Therefore, in this paper, depending upon the layer of operation of the instantaneous reference space vector, all the candidate vectors for the center of the subhexagon are generated, and the vector which is closest to the reference space vector is taken

as the center of the subhexagon.

A. Identifying the Layer of Operation

The instantaneous reference space vector can be resolved into the axes j_a , j_b , and j_c (Fig. 4) using the following where v_a , v_b , and v_c are the instantaneous amplitudes of the three

$$v_{j_a} = \sqrt{3}/2(v_a - v_c) \quad (1)$$

$$v_{j_b} = \sqrt{3}/2(v_b - v_a) \quad (2)$$

$$v_{j_c} = \sqrt{3}/2(v_c - v_b). \quad (3)$$

The axis lying in the 60° region which contains the instantaneous reference space vector will have maximum magnitude among these resolved values.

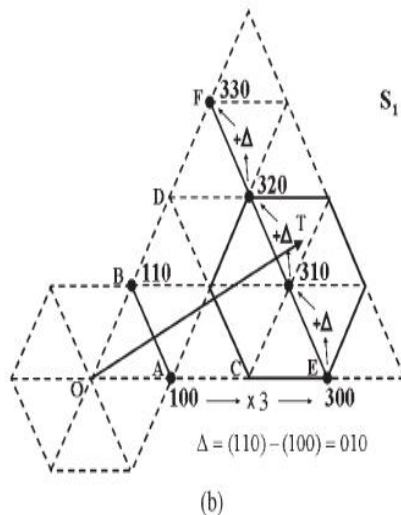
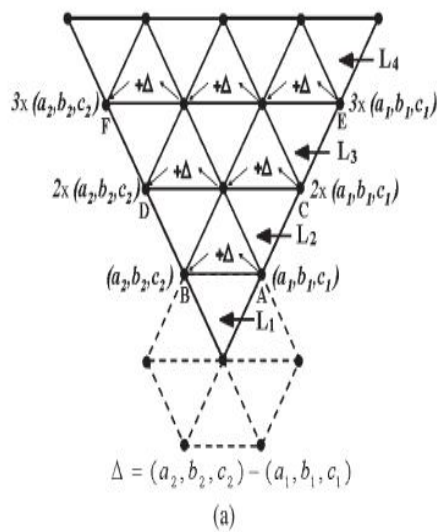


fig. 5. (a) Generating candidate vectors for the center of the subhexagon.
(b) Generating candidate vectors for the center of the subhexagon.

Let $v_{j_{\max}}$ be the maximum magnitude among the three resolved components. It may be noted that the width of each layer in the case of an n -level inverter is $((3/2)(V_{DC}/n - 1))$. Therefore, the layer number can be easily obtained as

$$m = 1 + \text{int} \left\{ \frac{v_{j_{\max}}}{\left(\frac{\sqrt{3}}{2} \frac{V_{DC}}{n-1} \right)} \right\} \quad (4)$$

Where m is the layer number

B. Generating Candidate Vectors for the Subhexagon Center

As already mentioned, in this paper, if the instantaneous reference space vector is in a particular layer m , then the candidate vectors for the center of the subhexagon are the vectors lying on the inner side of that particular layer. Fig. 5(a) shows a 60° region in the space vector diagram of a five-level inverter. In the figure, the lines AB, CD, and EF are part of the inner sides of layers 2, 3, and 4, respectively. It may be noted that AB, which is the inner side of layer 2, is Let the vectors on the inner side of layer 2 for any 60° region be (a_1, b_1, c_1) and (a_2, b_2, c_2) and the end vectors on the inner side of layer m be (a_{m1}, b_{m1}, c_{m1}) and (a_{m2}, b_{m2}, c_{m2}) . Then, the end vectors on the inner side of layer m can be generated as

$$(a_{m1}, b_{m1}, c_{m1}) = (m - 1) \times (a_1, b_1, c_1)$$

$$(a_{m2}, b_{m2}, c_{m2}) = (m - 1) \times (a_2, b_2, c_2). \quad (5)$$

The other vectors between the end vectors can be generated by repeatedly adding a difference vector “ Δ ” (the difference between the end vectors of the inner subhexagon) to the first end vector. The difference vector can be found out by subtracting the first end vector from the last end vector of the inner subhexagon

$$\Delta = (a_2, b_2, c_2) - (a_1, b_1, c_1). \quad (6)$$

Repeated addition of the difference vector with the first end vector on the inner side of layer m for $m - 1$ times can generate all vectors on the inner side of the layer m .

Thus, all the vectors on the inner side of a particular layer can be automatically generated from the vectors of the inner subhexagon. Of these candidate vectors, the vector which is closest to the reference space vector is chosen as the center of the subhexagon containing the instantaneous reference space vector. The closest candidate vector can be easily determined by calculating a distance term “ d ” with respect to each of the candidate vector. The distance term indicates the distance of the candidate vector from the reference space vector. The distance term for the i th candidate vector can be calculated as

$$d_i = |v_\alpha - \alpha_{cv}| + |v_\beta - \beta_{cv}| \quad (7)$$

where the (v_α, v_β) and $(\alpha_{cv}, \beta_{cv})$ are the coordinates of the reference space vector and candidate vector, respectively. The candidate vector with the smallest distance term is the vector closest to the reference space vector and hence taken as the center of

subhexagon.

To illustrate this technique, Fig. 5(b) shows the instantaneous reference space vector lying in layer 4 ($m = 4$) and within the S_1 region. The inner side of layer 4 is EF. The vectors on the inner side of layer 2 in this case are 100 and 110, and the difference vector is $110 - 100 = 010$. The end vectors of EF can be determined as 300 and 330 by multiplying 100 and 110 with 3 as per (5). The repeated addition of the difference vector three times to the first end vector 300 will generate the vectors 310 ($300+010$), 320 ($310+010$), and 330 ($320+010$) for the inner side of layer 4.

Of these candidate vectors on the inner side of layer 4, the closest vector to the reference space vector OT is 310, and it is chosen as the center of the subhexagon associated with OT .

IV. GENERATION OF SWITCHING VECTORS AND OPTIMUM SEQUENCE

In the proposed method, the actual vectors to be switched by the inverter are generated through the principle of mapping. subhexagon that contains the tip of the reference space vector is mapped to the inner subhexagon by subtracting the vector located at the center of the subhexagon.

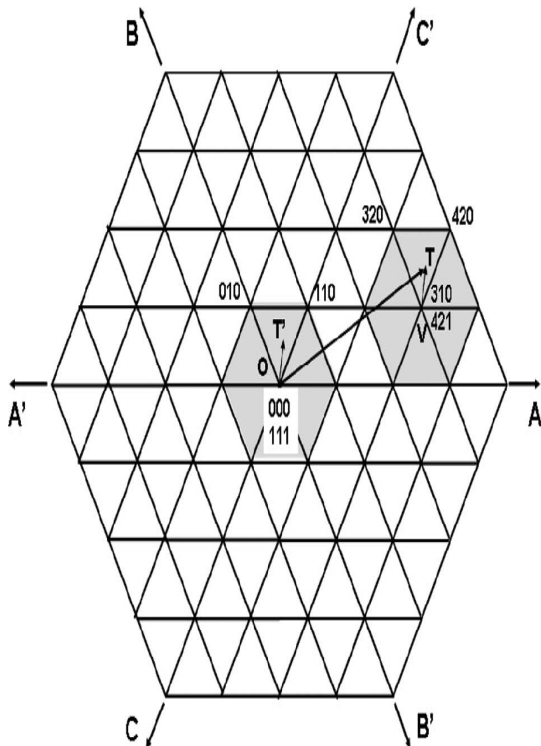


Fig. 6. Switching vector generation through reverse mapping.

For an n -level inverter, if v_α and v_β are the coordinates

of the instantaneous reference space vector OT and (α_c, β_c) is the coordinate of the center of the subhexagon containing OT , the coordinates (v_α^s, v_β^s) of the mapped vector OT^s are

$$\begin{aligned} v_\alpha^s &= v_\alpha - \alpha_c \\ v_\beta^s &= v_\beta - \beta_c \end{aligned} \tag{8}$$

Since the inner subhexagon corresponds to the basic two-level structure, the switching vectors of the two-level inverter can be generated from the instantaneous amplitude of the phase voltages [25].

The vectors of the two-level inverter can be translated to the actual switching vectors (corresponding to the multilevel inverter) by reverse mapping the inner subhexagon to the sub-hexagon containing the tip of the reference space vector. This reverse mapping can be easily done by adding the vector at the center of the subhexagon to the instantaneous switching vectors of the two-level inverter.

If (a_0, b_0, c_0) is the instantaneous switching vector corresponding to the two-level inverter and (a_c, b_c, c_c) is the vector at the center of the subhexagon, then the actual switching vector of the multilevel inverter is

$$(a_m, b_m, c_m) = (a_0, b_0, c_0) + (a_c, b_c, c_c) \tag{9}$$

Equation (9) defines the reverse mapping proposed in this paper whereby the two-level inverter vectors are translated to the vectors of the multilevel inverter. Therefore, the actual vectors to be switched and the optimum sequence are automatically generated without using lookup tables.

Continuing with the previous example, Fig. 6 shows the reference space vector OT mapped as OT^s to the inner sub-hexagon by subtracting the vector 310. Once the reference space vector is mapped to the inner subhexagon, two-level SVPWM techniques can be employed for generating the two-level vectors in optimum sequence. The two-level inverter switching vectors in optimum sequence are determined using a two-level SVPWM technique, which will be similar to that of a conventional two-level inverter, i.e., $000 \Rightarrow 010 \Rightarrow 110 \Rightarrow 111$ (Fig. 6). These two-level inverter vectors can be translated to the actual inverter voltage vectors of the multilevel inverter by the reverse mapping defined by (9).

Since the center of the subhexagon is 310, the actual inverter voltage vectors to be switched are $310(000 + 310) \Rightarrow 320(010 + 310) \Rightarrow 420(110 + 310) \Rightarrow 421(111 + 310)$.

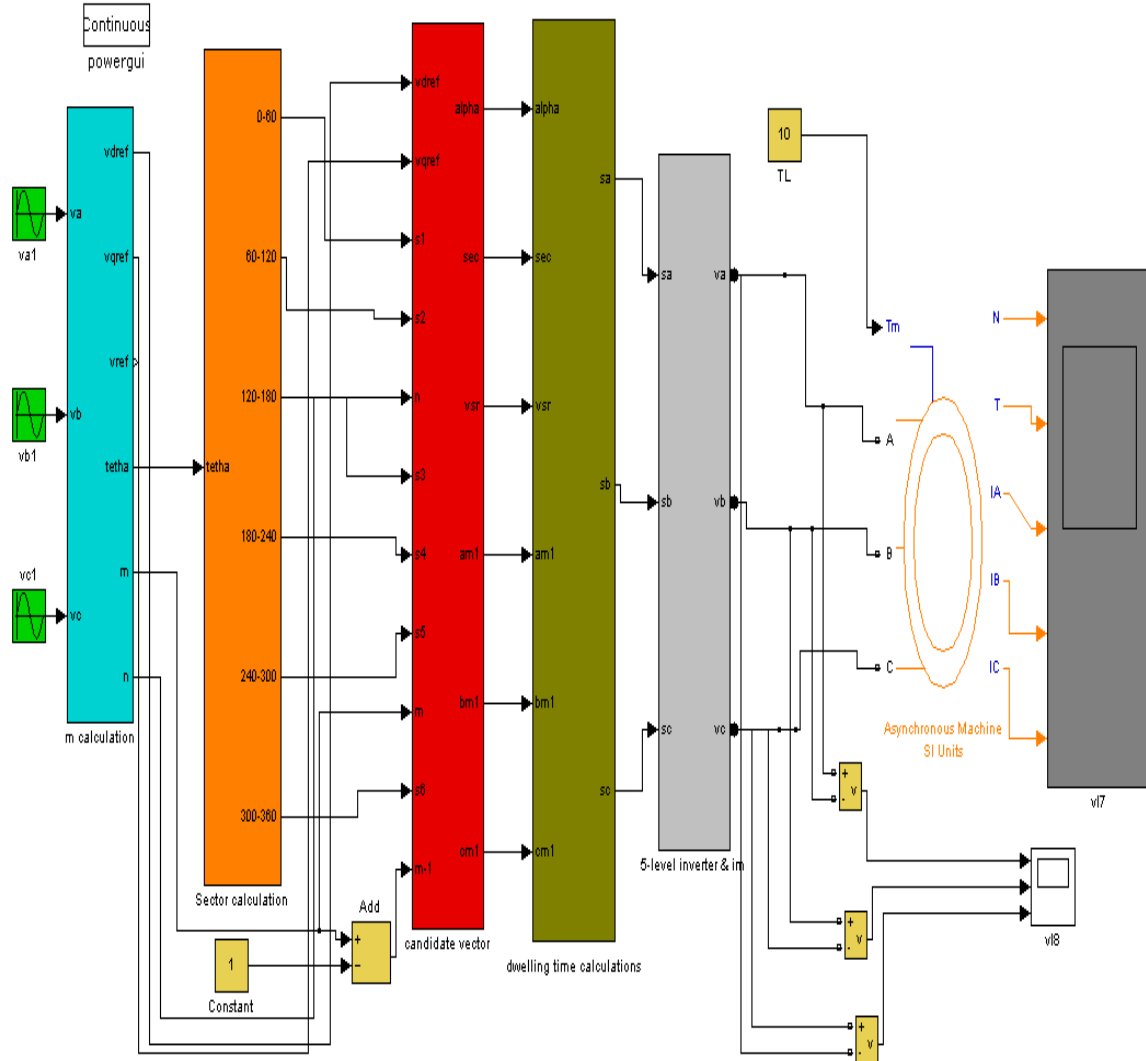
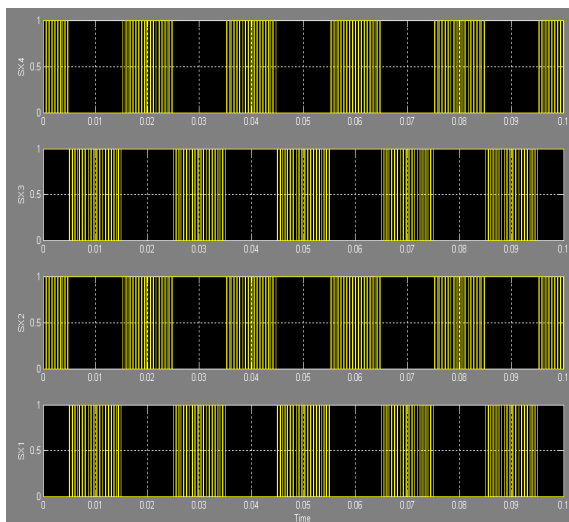


Fig 7: Main block diagram

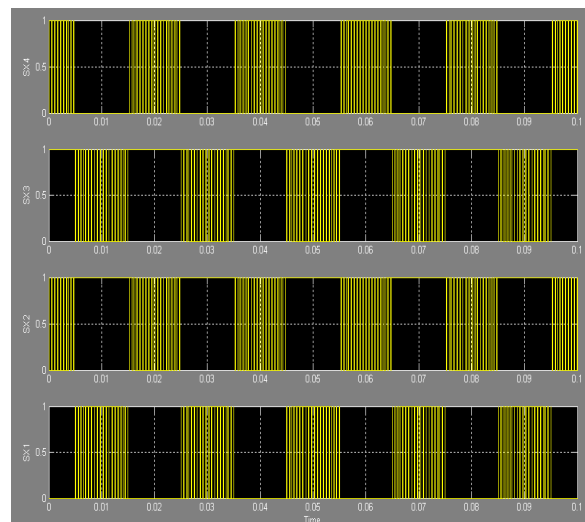
Experimental Results

3- Level Results

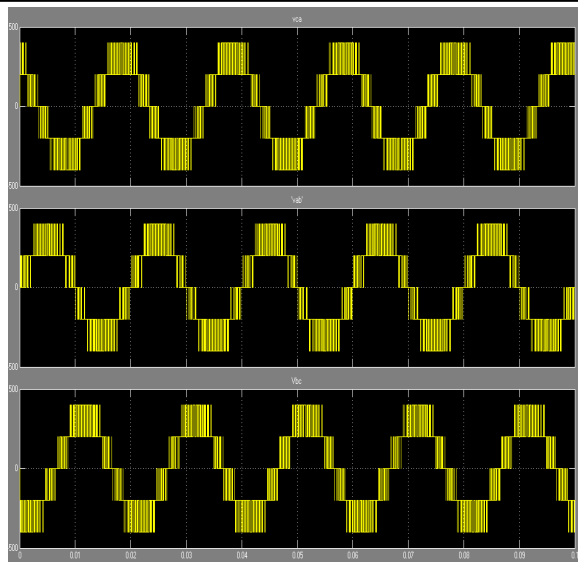


Graph 1(a): Gate Pulse for 3 level inverter

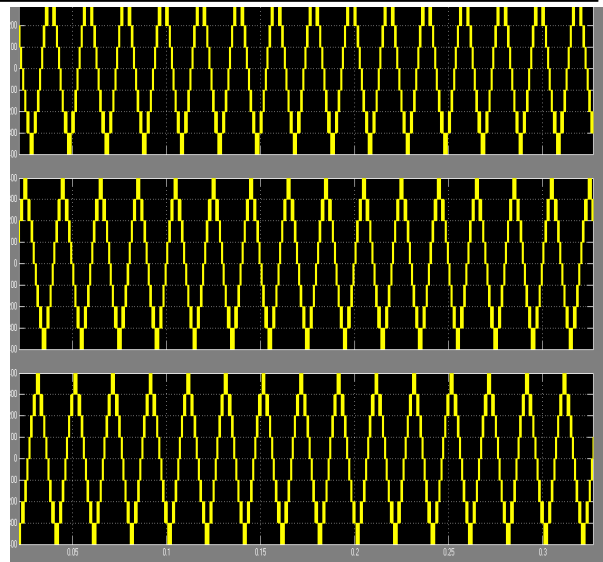
5- Level Results



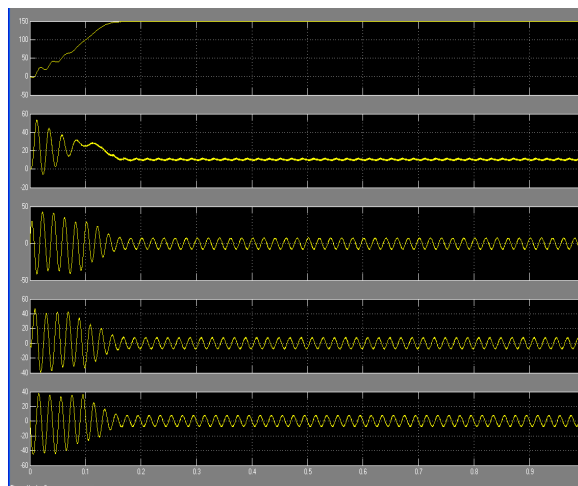
Graph 1(b): Gate Pulse for 5 level inverter



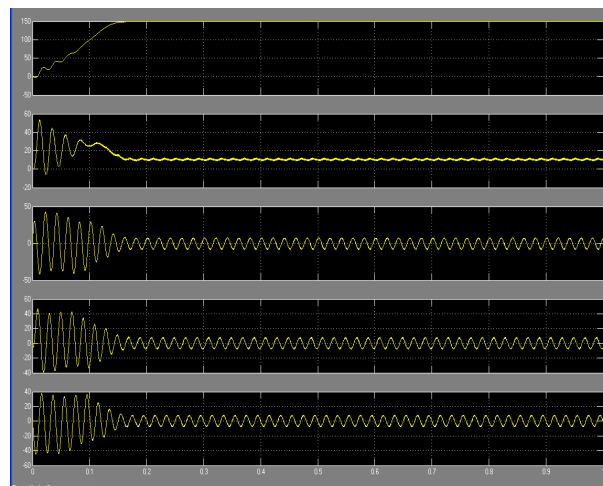
Graph 2(a) :3- Level Line Voltages



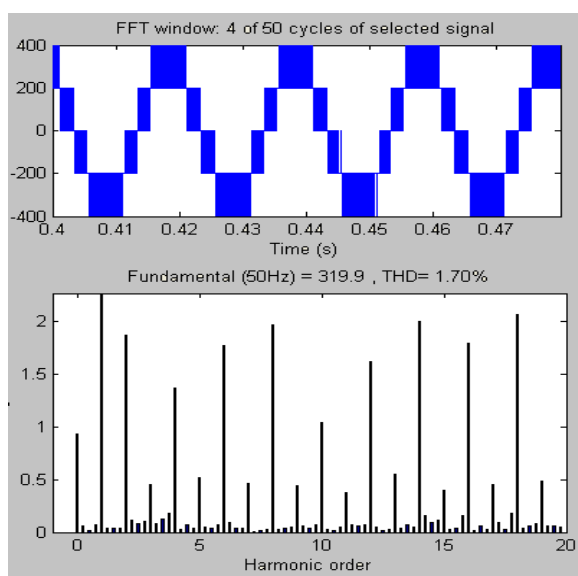
Graph 2(b): 5- Level Line Voltages



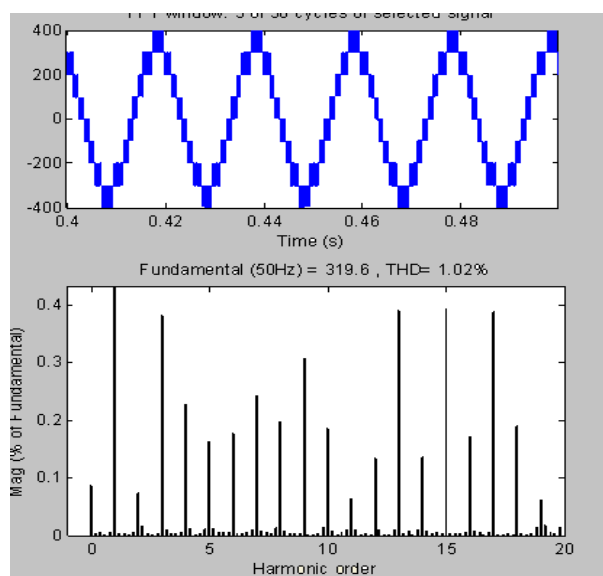
Graph 3(a) : Induction Motor Paramiters(ω_n , T_e , I_a , I_b , I_c)



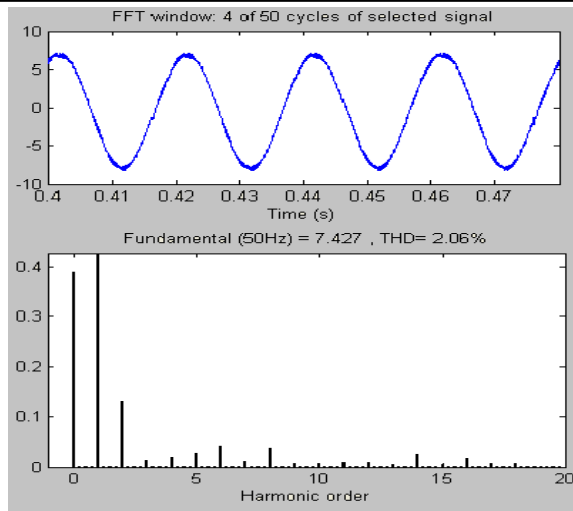
Graph 3(b) : Induction Motor Paramiters(ω_n , T_e , I_a , I_b , I_c)



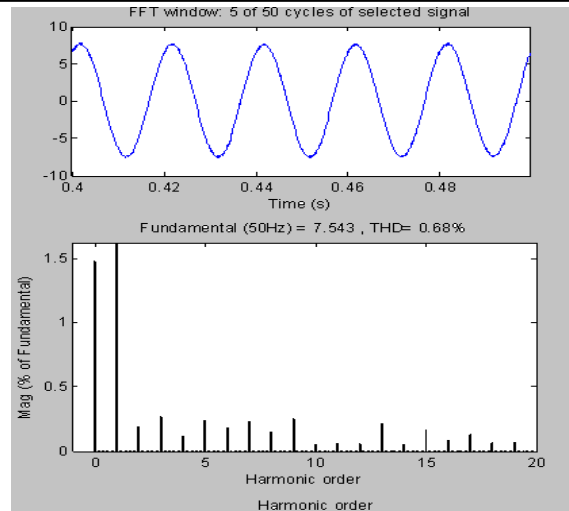
Graph 4(a): 3-Level Voltage THD



Graph 4(b): 5-Level Voltage THD



Graph 5(a): 3-Level Current THD



Graph 5(b): 5-Level Current THD

V. CONCLUSION

A novel SVPWM scheme has been presented for multilevel inverters. The switching vectors and optimum switching sequence are automatically generated by the principle of mapping. The vector at the center of the subhexagon containing the reference space vector was directly identified in this paper. The reference space vector is mapped to the innermost subhexagon, and the switching vectors for the two-level inverters are generated. The two-level inverter vectors are translated to the vectors of the multilevel inverter by the principle of *reverse mapping* proposed in this paper. The SVPWM for any n -level inverter including an inverter with an even number of levels can be implemented without any additional complexity. The proposed method does not identify the sector containing the reference space vector and eliminates the need of lookup tables for determining the switching vectors and the optimum sequence for a multilevel inverter. The proposed SVPWM scheme is implemented on a MATLAB platform, and experimental results are presented for a three-level inverter and five level inverter.

Induction Motor Details

Drive : Three phase squirrel cage induction motor

Specifications:

Horse Power : 5.4 (4 KW)

Line to line voltage : 400V

Frequency : 50Hz,

Speed : 1430

RPM

Block Parameters of three phase squirrel cage induction motor :

- 2) Resolve the reference space vector into the axes $j_a, j_b,$ and j_c using (1), (2), and (3).
- 3) Determine the layer of operation m using (4).
- 4) If ($m > n - 1$).
Overmodulation operation: $m = n - 1$, go to step 5). else: Normal operation: go to step 5).
- 5) Identify the 60° region "S" of the multilevel inverter by comparing the amplitudes of the three phase reference voltages and determine the end vectors (a_1, b_1, c_1) and (a_2, b_2, c_2) in the inner side of layer 2.
- 6) Calculate the first end vector (a_{m1}, b_{m1}, c_{m1}) of the inner side of layer m using (5).
- 7) Find the difference vectored as the difference of the vectors obtained in step 5) as in (6)
- 8) Starting from the first end vector, generate other vectors in the inner side of layer m by adding the difference vector repeatedly for " $m - 1$ " times to get the candidate vectors.
- 9) Choose the vector which is closest to reference space vector as the center of the subhexagon (a_c, b_c, c_c) by calculating the distance term d as in (7).
- 10) Map the reference space vector to the inner subhexagon and calculate the three instantaneous phase reference voltages of the mapped reference space vector by (8).
- 11) Generate the two-level switching vectors and the optimum switching sequence for the mapped reference space vector with the two-level SVPWM method.
- 12) Add the center of the subhexagon (a_c, b_c, c_c) obtained in step 9) to the two-level vectors to generate the switching vectors and optimum sequence for the multilevel inverter.

APPENDIX

Proposed Algorithm for an n -Level Inverter

- 1) Obtain the instantaneous values of three phase reference voltages $v_a, v_b,$ and v_c .

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