Space Vector Pulse Width Modulation in Wind Turbines' Generator Control

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Abstract— Three phase voltage source inverters supply variable voltage and frequency to alternating current machines. Pulse width modulation (PWM) is often used to transfer supply voltage from direct current (DC) into three-phase alternating current (AC) for operation of three-phase AC machines. Space vector pulse width modulation (SVPWM) is a computationally controlled PWM technique applied in industry for its efficient use of direct current voltage, low switching loss, low computational complexity, and high flexibility. We collected information from available sources in order to understand SVPWM and the particular qualities this type of PWM presents. An intuitive approach section, followed by space vector representation, mathematical reasoning, and modulation strategy sections clearly present information to the reader. The result is a well-rounded understanding of the SVPWM technique. SVPWM high switching rates lead undesirable total harmonic distortion rates. Research into methods of reducing this total harmonic distortion is suggested.

Index Terms— AC-DC power converters, pulse inverters, power conversion, and space vector pulse width modulation.

I. Introduction and Background

Kirnnich, Heinrick and Bowes first developed PWM in the mid 1960's [1]. Carrier based techniques developed first, followed by SPWM in 1964 by Schonung and Stemmler [2]. Not until the mid-1980's was SVPWM introduced [3]. This technique held strong advantages allowing for higher DC bus efficiency, voltage magnitude control, low power losses, and variable frequency control. Other advantages of SVPWM include a wide linear modulation range, low switching loss, easy implementation, and fewer computations due to the reduced number of sin functions. Advances in microprocessors decreased computation time further, leading SVPWM to become the preferred PWM technique.

PWM aims to control duty ratio of pulsating waveforms using an input waveform to calculate duty cycle of switches. Waveform control is based on modulated signal information. There are many approaches to the modulation of signal information with none performing best for all situations. We have chosen to focus on SVPWM due to its widespread use in industry. In SVPWM, the three phase variables are expressed in space vectors. Each desired voltage vector can be simulated by an averaging effect between two adjacent active vectors and a zero vector. Modulation strategy plays an important role in the minimization of harmonics and the switching losses in converters. The technique follows five set steps. First, phase angle and voltage reference vector is calculated based on input voltage components. Second, the modulation index is calculated and it is determined if the system is in the over modulation region. Third, the reference voltage vector section is found, as are the adjacent space vectors based on sector angle. Fourth, time intervals T_a, T_b, and T_o are calculated based on T_{source} and phase angle. Finally, for different switching states, the modulation times are calculated [4]. SVPWM is applied to output voltage and input current; the main objective being approximation of reference voltage vector utilizing eight switching patterns [5]. The most common application of SVPWM is to create three-phase AC from a DC supply using multiple class-D amplifiers for use in driving motors. This technique generates less harmonic distortion in output voltage and input current to AC motor, as well as provides advantages under unbalanced motor operation conditions leading it to be the PWM technique of choice.

One of the largest advantages of SVPWM algorithm for PWM is the increased efficiency of DC bus voltage use. SVPWM maximum peak fundamental magnitude of 90.6% of inverter capacity is 15.5% over SPWM [6]. In 1991, Holtz proposed over-modulation based SVPWM, further improving the DC bus voltage usage to the levels of six step waves [7, 8].

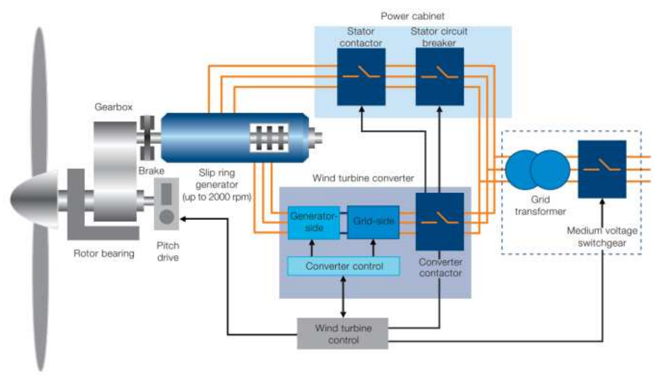

Fig. 1. Doubly Fed Induction Generator configuration for WTS [9]

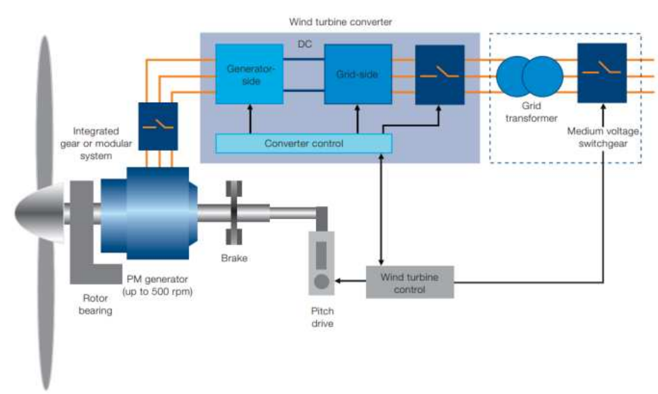

Fig. 2. Fully Rated Converter configuration for WTS [9]

II. Space Vector PWM – An Intuitive Approach

Fig. 1 and Fig. 2 show typical configurations for variable speed Wind Turbine Systems. In both cases, the generator side converter generates a 3-phase AC voltage from a DC supply to feed either into the stator (FSC) (Fig. 3) or into the rotor of the generator (DFIG). By controlling the magnitude and frequency of the output 3-phase AC voltage, the converter can control the torque of the generator to maximize energy harvesting from the wind. The 3-phase AC voltage can be constructed using various techniques. A modern technique popularly used in 3-phase inverters is Space Vector Pulse Width Modulation (SVPWM). In SVPWM, the 3-phase inverter (Fig. 3) is treated as a state machine. Two switches on the same leg cannot turn-on or turn-off at the same time, therefore, the state machine has eight states. Fig. 4 shows these eight states with a simplified circuit illustrating state one. Six of the eight states result in voltage applied to the generator windings with two states resulting in zero voltage. Fig. 5 illustrates directions and amplitudes of the space vector voltages applied to the generator corresponding to the six active states. These vectors inform us of the direction that the inverter is attempting to establish a magnetic field inside the generator. To control the torque output of the generator, we need to create a smoothly rotating vector. The inverter must have the ability to establish a vector at any angle, not just the six vector shown in Fig. 5.

By switching between two adjacent vectors quickly, the generator will see an average vector somewhere in-between the two switching vectors. The filter between the inverter and the generator (Fig. 3) will filter out the high frequency effect caused by the switching. For example, in the space vector diagram in Fig. 5, if we spend an equal amount of time switching between vector V1 at 0^{o} and V2 at 60^{o}, the resulting average vector will be 30^{o}. If we spend more time with V1 activated than V2, the average vector will closer to V1. By controlling the switching time, we can create an average vector at any angle between V1 and V2. Similarly, switching between V2 and V3 we can create an average vector at any angle in sector 2 (Fig. 5), and so on. In this way we can output an average vector at any angle we want using just the six vectors in Fig. 5, and we can rotate it smoothly.

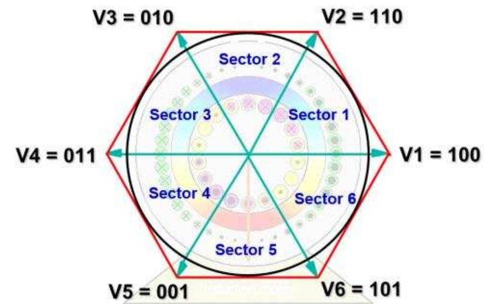

Fig. 5. Six voltage vectors inside the generator resulting from state 1 to 6 of the inverter.

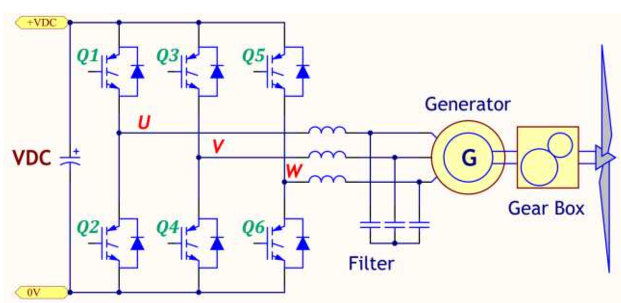

Fig. 3. Two-Level Voltage-Source Inverter

State	Q1	Q2	Q3	Q4	Q5	Q6	Sa	Sb	Sc
0	0	1	0	1	0	1	0	0	0
1	1	0	0	1	0	1	1	0	0
3	0	1	1	0	0	1	0	1	0
2	1	0	1	0	0	1	1	1	0
5	0	1	0	1	1	0	0	0	1
6	1	0	0	1	1	0	1	0	1
4	0	1	1	0	1	0	0	1	1
7	1	0	1	0	1	0	1	1	1

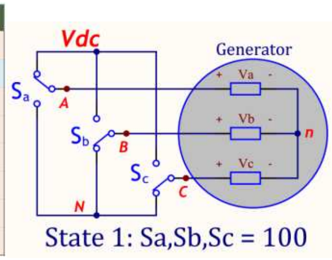

Fig. 4. Eight useful states of the inverter with a simplified circuit illustrating

III. Space Vector Representation of 3-Phase System

The traditional single-phase equivalent phasor circuit model is useful in analyzing electrical machines in sinusoidal steady state operations. However, the model is not sufficient to understand electrical machines in transient states, which happen when the machine is starting up or trying to balance out external forces. The space-vector theory was developed to remedy this by providing a better understanding, and thus more precise control of electrical machines.

Vector representation of 3-phase systems were first introduced in 1929 by Park [11] and later improved by Kron in 1942 [12]. Kovacs and Racz performed a detailed mathematical treatment and physical explanation for Space Vector theory to help understand transient responses of electrical machines in 1959 [13]. In the early seventies Stepina and Serrano introduced the concept of a "Space Phasor" instead of "Space Vector" as a better tool for analyzing electrical machines [14,15]. Nowadays, "Space Phasor" is mainly used for current and flux analysis of electrical machines [16].

A. Space vectors representation of 3-phase systems – an introduction.

A simplified two-dimensional representation of the magnetic axis of a two-pole three-phase machine is found in Fig. 6. Each phase winding produces a sinusoidal flux density in the air gap. In order to simplify calculations, we assume several things: the air gap flux density is sinusoidal, the saturation of the magnetizing circuit is constant, there are no core losses, and resistance/inductances are independent of the temperature and

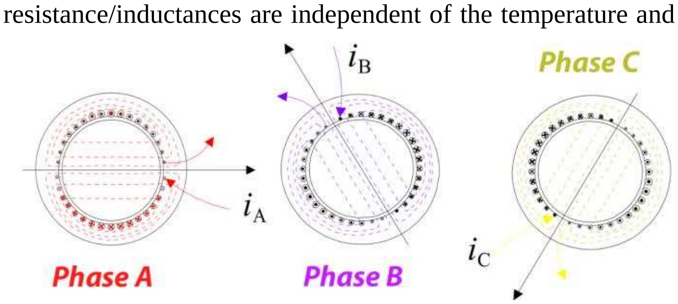

Fig. 6. The magnetic axes of a two-pole three-phase machine [10].

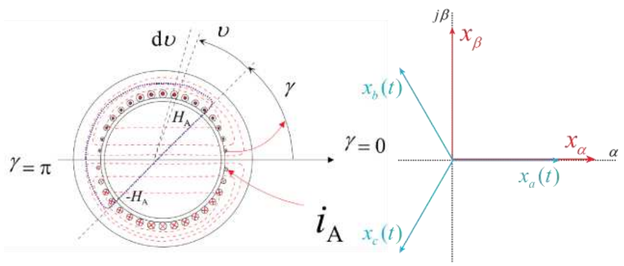

Fig. 7. The magnetic axes of a two-pole three-phase machine [10].

frequency.

The magnetomotive force created by each phase can be calculated by applying Ampere's law to a closed path in Fig. 7:

$$F_a = N_s i_A \cos\gamma \tag{1}$$

$$F_b = N_s i_B \cos(\gamma + \frac{2\pi}{3})$$

$$F_c = N_s i_C \cos(\gamma + \frac{4\pi}{3})$$

The total magnetomotive force, sum of $\overrightarrow{F_a}, \overrightarrow{F_b}, \overrightarrow{F_c}$, can be represented by a space vector expressed in the α, β complex plane attached to the stator (Fig. 7):

$$\begin{aligned}\overline{F}_{stator} &= F_a + F_b\angle 120 + F_c\angle 240 \\ &= F_a + F_b e^{j2\pi/3} + F_c e^{j4\pi/3} \\ &= F_a + \overline{a}F_b + \overline{a}^2 F_c\end{aligned} \tag{2}$$

With $\overline{a} = e^{j2\pi/3}$ representing the positive rotation of 120 degrees.

According to eq.1, the magnetomotive forces are created by phase currents. Similarly, we can imagine that the total force space vector $\overline{F}_{stator}$ is created by a space vector current $\overline{i}_{stator}$, which represents the total effect of the 3-phase current i_A, i_C, i_C.

$$\overline{F}_{stator} = N_s \overline{i}_{stator} \tag{3}$$

From eq. 1, eq. 2 and eq. 3, we have:

$$\overline{i}_{stator} = i_a + \overline{a}i_b + \overline{a}^2 i_c \tag{4}$$

In the case of sinusoidal steady state phase current, we have:

$$\begin{aligned}\overline{i}_{stator} &= I_m \sin(\omega t) + \overline{a}I_m \sin(\omega t + \frac{2\pi}{3}) + \overline{a}^2 I_m \sin(\omega t + \frac{4\pi}{3}) \\ &= \frac{3}{2} I_m(\cos(\omega t) + j\sin(\omega t)) = \frac{3}{2} I_m e^{j(\omega t)}\end{aligned} \tag{5}$$

Eq. 5 shows that the current space vector rotates with the same angular frequency of phase currents. The amplitude of the space vector is equal to 3/2 of the peak value of the sinusoidal phase current i_A, i_C, i_C. In order to make use of the old equivalent phasor circuit model and machine parameters such as the resistances, inductances, and rated power, the space vector is scaled by the factor of 2/3 in most literatures. However, some literatures use scale factor $\sqrt{2/3}$ and a very few literatures do not scale at all. This is a source of confusion.

Space vector indicates a vector in the space inside an electrical machine. It was first developed to analyze electrical machines, but was later generalized to the study any 3-phase system. Although they make use of the same machine parameters, space vectors and space phasors are very different. Space vector is a simultaneous representation of three-phase quantities as a function of time. This is in contrast to the space phasor, which is not based on time. Space vector models simplify the representation and the calculation of 3-phase systems, especially in asymmetrical 3-phase systems.

B. Space vector formal definition:

Space vector representation of 3-phase quantities $x_a(t)$, $x_b(t)$, $x_c(t)$ is given by a vector in the α, β complex plane [16]:

$$\overline{x} = x_\alpha + jx_\beta = \frac{2}{3}\left(x_a(t) + \overline{a}x_b(t) + \overline{a}^2 x_c(t)\right) \tag{6}$$

Where a is the positive rotation $2\pi/3$: $a = e^{j2\pi/3} = -1/2 + j\sqrt{3}/2$

The α, β components of the space vector can also be achieved by Clarke transform:

$$\overline{x} = \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{bmatrix}$$

C. Space vector output of 3-phase inverter:

The 3-phase inverter in Fig. 8 is herein considered. As previously discussed, the inverter has eight useful switching states. Six of the eight states result in voltages applied to the generator windings with two states resulting in zero voltage.

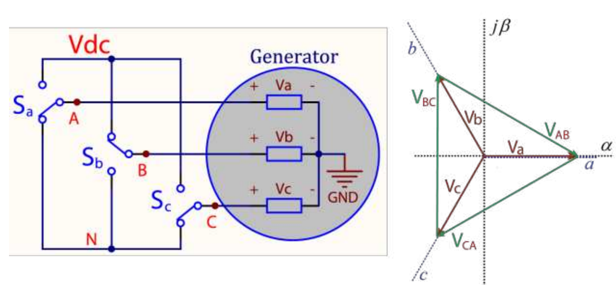

Fig. 8. The 3-phase inverter and the α, β complex plane.

The voltage output of the inverter can be represent by a space vector $\bar{v}$ in the α, β complex plane (Fig. 8). This vector is calculated by phase voltages using eq. 6:

$$\bar{v} = \frac{2}{3}(v_a + \bar{a}v_b + \bar{a}^2 v_c) \tag{7}$$

Where v_a, v_b, v_c are the output phase voltages of the inverter.

According to KVL, we have:

$$v_a = v_{AN} + v_N,\ v_b = v_{BN} + v_N,\ v_c = v_{CN} + v_N$$

Replacing these into eq. 7:

$$\begin{aligned}\bar{v} &= \frac{2}{3}[(v_{AN} + v_N) + (v_{BN} + v_N)\bar{a} + (v_{CN} + v_N)\bar{a}^2] \\ &= \frac{2}{3}[v_{AN} + v_{BN}\bar{a} + v_{CN}\bar{a}^2 + v_N(1 + \bar{a} + \bar{a}^2)]\end{aligned}$$

Since $1 + \bar{a} + \bar{a}^2 = 1 + e^{j2\pi/3} + e^{j4\pi/3} = 0$, we have:

$$\bar{v} = \frac{2}{3}(v_{AN} + v_{BN}\bar{a} + v_{CN}\bar{a}^2)$$

With the state of each switch, $S_a; S_b; S_c$ equal to 0 or 1, we have: $v_{AN} = V_{dc}S_a; v_{BN} = V_{dc}S_b; v_{CN} = V_{dc}S_c$;

$$\bar{v} = \frac{2}{3}V_{dc}(S_a + \bar{a}S_b + \bar{a}^2 S_c) \tag{8}$$

The output voltage space vector $\bar{v}$ corresponding to the eight states of the inverter are depicted in Fig. 9.

State	S_a	S_b	S_c	Vector	$\frac{2}{3}V_{dc}(S_a + aS_b + a^2S_c)$	$\bar{v}$
0	0	0	0	$\bar{v}_0$	0	0
1	1	0	0	$\bar{v}_1$	$\frac{2}{3}V_{dc}$	$\frac{2}{3}V_{dc}e^{j0}$
2	1	1	0	$\bar{v}_2$	$\frac{2}{3}V_{dc}(1+a)$	$\frac{2}{3}V_{dc}e^{j(\pi/3)}$
3	0	1	0	$\bar{v}_3$	$\frac{2}{3}V_{dc}a$	$\frac{2}{3}V_{dc}e^{j(2\pi/3)}$
4	0	1	1	$\bar{v}_4$	$\frac{2}{3}V_{dc}(a+a^2)$	$\frac{2}{3}V_{dc}e^{j(3\pi/3)}$
5	0	0	1	$\bar{v}_5$	$\frac{2}{3}V_{dc}a^2$	$\frac{2}{3}V_{dc}e^{j(4\pi/3)}$
6	1	0	1	$\bar{v}_6$	$\frac{2}{3}V_{dc}(1+a^2)$	$\frac{2}{3}V_{dc}e^{j(5\pi/3)}$
7	1	1	1	$\bar{v}_7$	$\frac{2}{3}V_{dc}(1+a+a^2)$	0

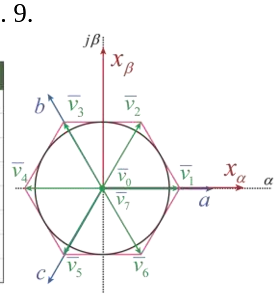

Fig. 9. Voltage space vector corresponding to eight states of the inverter

This result can be generalized into:

$$\bar{v}_k = \begin{cases} \frac{2}{3}V_{dc}e^{j(k-1)\frac{\pi}{3}} & \text{if } k = 1..6 \\ 0 & \text{if } k = 0, 7 \end{cases} \tag{9}$$

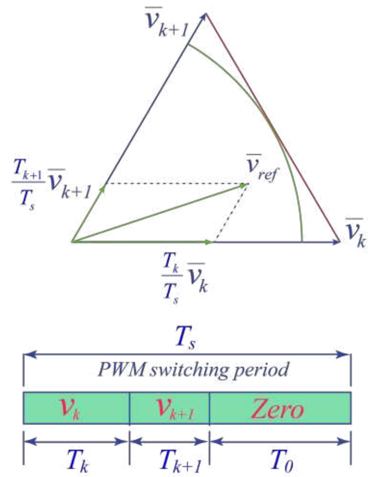

Fig. 10. The reference voltage vector v_{ref} is resolved by time-averaging of the nearest two active switching vectors.

IV. Space Vector Pulse Width Modulation (SVPWM)

In Vector control, the current controller calculates a reference voltage space vector $\bar{v}_{ref} = v_\alpha + jv_\beta$. Then, by SVPWM technique, the reference voltage vector $\bar{v}_{ref}$ is resolved by time-averaging the nearest two active switching vectors:

$$\bar{v}_{ref} = v_\alpha + jv_\beta = \frac{T_k}{T_s}\bar{v}_k + \frac{T_{k+1}}{T_s}\bar{v}_{k+1} \qquad \text{with } k = 1...6$$

With:

T_s : PWM switching period. $T_s = T_k + T_{k+1} + T_0$,

T_k : Duration inverter output vector $\bar{v}_k$

T_{k+1} : Duration inverter output vector $\bar{v}_{k+1}$

T_0 : Duration inverter output zero voltage.

Replacing $\bar{v}_k$ from (eq. 9) and solving for T_k, T_{k+1} we have:

$$\begin{bmatrix} T_k \\ T_{k+1} \end{bmatrix} = \frac{\sqrt{3}T_s}{V_{dc}} \begin{bmatrix} \sin\frac{k\pi}{3} & -\cos\frac{k\pi}{3} \\ -\sin\frac{(k-1)\pi}{3} & \cos\frac{(k-1)\pi}{3} \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{10}$$

With $k = 1...6$ as the sector number.

V. Modulation Strategies

As we previously discussed, in order to create an output voltage vector $\bar{v}_{ref}$, the inverter needs to output $\bar{v}_k$ for a duration T_k, $\bar{v}_{k+1}$ for a duration T_{k+1}, and zero voltage for the remaining time over one PWM switching period, T_s. The order of applying switching space vectors is referred to as the modulation strategy. In this section, we introduce the two most popular modulation strategies: symmetrical PWM sequence and discontinuous space vector PWM sequence.

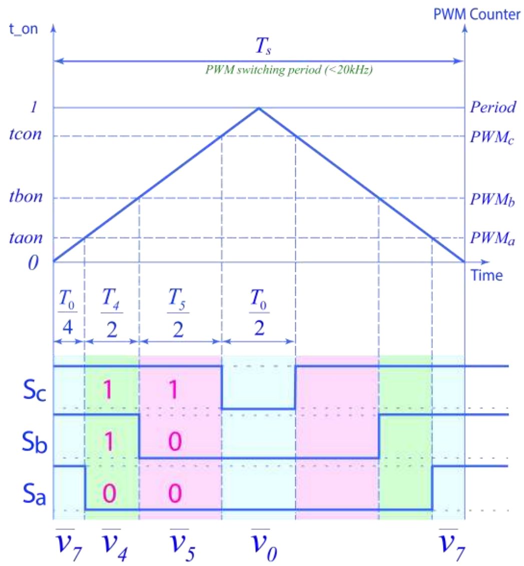

Fig. 11. Symmetrical PWM sequence.

A. Symmetrical PWM sequence

Symmetrical PWM Sequence (with $\overline{\text{v}}_{\text{ref}}$ in sector 4, k=4) is depicted in Fig. 11. The advantage of this modulation strategy is low THD resulting from its symmetry and because both zero vectors $\overline{\text{v}}_0, \overline{\text{v}}_7$ are used in one PWM cycle while there is only one leg of the inverter switching at a time.

B. Discontinuous Space Vector PWM sequence:

Discontinuous Space Vector PWM sequence is depicted in Fig. 12 (with $\overline{\text{v}}_{\text{ref}}$ in sector 1, k=1). This modulation strategy keeps one of the three legs off during the entire 120 degree. The advantage of this modulation strategy is low switching loss due to fewer switchings per PWM cycle. The drawback of this modulation strategy is high harmonic output.

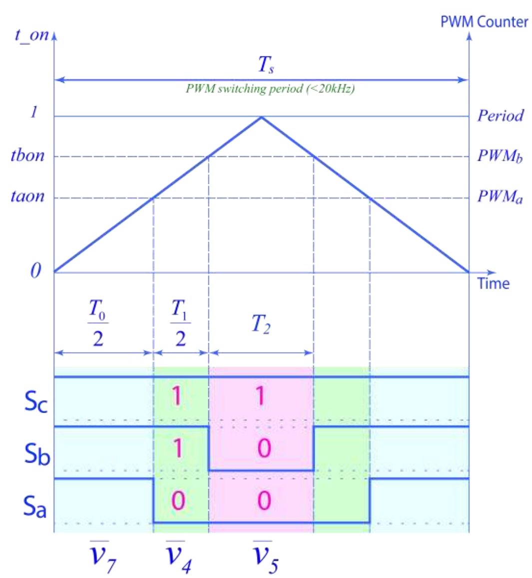

Fig. 12. Discontinue PWM sequence.

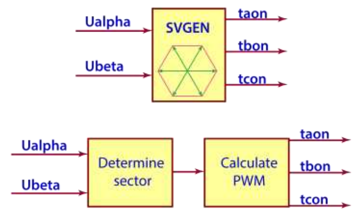

Fig. 13. SVPWM generation firmware block implementation in MCU.

VI. SVPWM Algorithm for Microcontrollers

The implementation of SVPWM generation firmware block in a microcontroller (Fig. 13) normally takes the input U_α, U_β components of the reference voltage vector and outputs $t_{a,on}$, $t_{b,on}$, and $t_{c,on}$. These three output numbers represent the on time of the three switches (a, b, c). If the calculation is done in floating point the values normally range from 0 to 1, but if the calculation is done in integer form the values will be scaled to a specific global maximum. In integer form, saturation can be done in the input (U_α, U_β), in the output values (taon, tbon, tcon), or both.

The SVPWM generation block can be divided into 2 steps (Fig. 13): (a) finding the reference voltage vector sector (b) Calculate PWM values (or t_on).

A. Determine sector for $\overline{\text{v}}_{\text{ref}}$

The determination of location sector of $\overline{\text{v}}_{\text{ref}}$ can be done in many ways. We found the easiest way is to look at the sign of the voltage in phase a, b, c of the reference votage vector $\overline{\text{v}}_{\text{ref}}$. This method is found in Texas Instruments's reference code for C2000 MCU [17]:

```
uint16_t Sector = 0; // Sector
// 60 degree Sector determination
if (Va > 0) Sector = 1;
if (Vb > 0) Sector = Sector+2;
if (Vc > 0) Sector = Sector+4;
```

Other method is to look at the sign of $\text{v}_\alpha; \text{v}_\beta$ and $\text{v}_z = \text{v}_\beta - \sqrt{3}\text{v}_\alpha$. This method is found is Freescale's reference code for Kinetis MCU [18]:

	$v_\beta >= 0$			$v_\beta < 0$		
	$v_z < 0$	$v_z >= 0$		$v_z < 0$		$v_z >= 0$
		$v_\alpha >= 0$	$v_\alpha < 0$	$v_\alpha >= 0$	$v_\alpha < 0$	
Sector	1	2	3	6	5	4

The method from Freescale require less computation and memory than the Texas Instruments method. In the first method we need to do inverse Clarke transform to obtain Va, Vb, Vc from $\overline{\text{v}}_{\text{ref}}$, while the second method only requires us to calculate $\text{v}_z = \text{v}_\beta - \sqrt{3}\text{v}_\alpha$. This value can also be used later in PWM value calculation, further reducing total computational requirement.

B. Calculate PWM values for switches

The PWM values for the three switch S_a, S_b, S_c can be calculated in various ways. We are presenting the most popular method found in reference codes from: Texas Instruments, Freescale, Microchip, Atmel, Infineon, etc.

The reference vector $\bar{v}_{ref}$ is scaled to $\sqrt{3}/V_{dc}$ before sending it to the SVPWM block.

$$\bar{U}_{ref} = \frac{\sqrt{3}}{V_{dc}} \bar{v}_{ref} \quad \Leftrightarrow \quad \begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = \frac{\sqrt{3}}{V_{dc}} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}$$

To simplify calculation, we call X, Y, Z:

$$X = U_\beta \; ; \; Y = \frac{(U_\beta + \sqrt{3}U_\alpha)}{2} \; ; \; Z = \frac{(U_\beta - \sqrt{3}U_\alpha)}{2}$$

Use eq. 10 to calculate T_k and T_{k+1} for six active sectors. We have:

k	T_k	T_{k+1}	$t_a=T_k/T_s$	$t_b=T_{k+1}/T_s$
1	$-Z*T_s$	$X*T_s$	-Z	X
2	$Y*T_s$	$Z*T_s$	Y	Z
3	$X*T_s$	$-Y*T_s$	X	-Y
4	$Z*T_s$	$-X*T_s$	Z	-X
5	$-Y*T_s$	$-Z*T_s$	-Y	-Z
6	$-X*T_s$	$Y*T_s$	-X	Y

Particularly, using symmetrical PWM sequence strategy, in sector 4, (Fig. 11) (with k=4) we have:

$$taon = \frac{T_0}{2T_s} = \frac{T_s - T_k - T_{k+1}}{2T_s} = \frac{1 - t_a - t_b}{2}$$

$$tbon = taon + t_a$$

$$tcon = tbon + t_b$$

The calculation is similar for other sectors. From this calculation, the code for sector 4 can be written:

```
switch(Sector){
   case 4:  //Sector 4: ta=Z and tb=-X
      ta = Z;
      tb = -X;

      taon = ((1-ta-tb) * 0.5f);//taon= (1-ta-tb)/2
      tbon= taon + ta;         //tbon=taon+ta
      tcon = tbon + tb;        //tcon= on+tb
      break;
}
```

VII. Conclusion

This paper has gathered the SVPWM knowledge from inception to current day in order to provide an accurate representation of this increasingly common and important PWM technique. The phasor and vector sections provide the reader with the background to assist in the comprehension of SVPWM theory and mathematics comprising thereof. This technique continues to be one of the most popular in industry for its increased current bus utilization, frequency control, and low switching loss. Total harmonic distortion problems with SVPWM technique remain. To increase the future field of applications for this technique, further research into reducing total harmonic distortion is suggested.

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