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Implementing Multi-Phase Space-Vector Modulation

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Implementing Multi-Phase Space-Vector Modulation

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Chencheng Hu

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Abstract

Implementing Multi-Phase Space-Vector Modulation

By Chencheng Hu

Recently there has been growing interest in multi-phase motors and drives due to their potential advantages including lower torque ripple and harmonic currents, better power density, higher reliability and stability. Two commonly used modulation methods space-vector modulation and sine-triangle modulation are proposed for using in multi-phase induction motors. In this paper, the implementation details of producing random switching patterns are presented by using MATLAB/Simulink. The simulation results are shown for three-level five-phase induction motor. Add current harmonics in the sine-triangle modulation based on the result of SVM. Finally, compare their torque ripples and show the further optimized scheme.

Keywords: Three-level five-phase, SVM, Sine-triangle modulation, switching pattern, torque ripple

1.INTRODUCTION

In electrical applications, three-phase motor dives are widely used. Recently, multi-phase induction machines have been used in applications such as ship propulsion, electric aircraft, and electric/hybrid vehicles. Some published works have shown that multiphase drive systems have advantages compared to traditional three phase systems such as lower torque ripple, higher power density, improved reliability, reduced current harmonics, etc. [1-3] In order to implement multi-phase motor drives, researchers have proposed some methods in multiphase drive systems. These techniques can generally be classified into two categories: space-vector modulation (SVM), and sine triangle modulation [4]. For SVM, a vector space decomposition algorithm has been proposed. By using this method, a two-level space vector PWM can be decomposed into d_1-q_1 vector space and d_2-q_2 vector space. Where d_3-q_3 typically need to be null to maintain a sinusoidal flux pattern in the five-phase induction motor [5-8]. For three-level five-phase SVM, reference [9] presented a nearest three vector algorithm. However, this method cannot satisfy the requirement which d_3-q_3 needs to be null and it also does not take the switching loss into consideration. A novel algorithm for three-level five phase SVPWM technique is developed in reference [1]. In this method, five vectors were used to produce the switching sequences. This method can eliminate the output voltage distortion caused by the d_3-q_3 voltage component and reduce power losses. However, the torque ripple cannot be minimized in this model. Reference [10] proposed a walking pattern SVM technique with using some fixed switching sequences so that the method can minimize the torque ripple. It is a trade-off analysis for SVPWM. Switching loss, voltage distortion and the torque ripple cannot be optimized at the same time.

Sine-triangle modulation is another common technique used in multi-phase drive systems. In a three-level PWM systems, reference voltage is compared with two identically triangle waveforms. The switching frequency is controlled by the frequency of carrier, and the amplitude of the output voltage was controlled by the modulation index of the sinewave [11].

There is no consensus on which modulation method is the best. They both have their own advantages. The sine-triangle modulation is more efficient and flexible in practice, and the SVM can control the switching pattern to obtain better harmonic performance [12]. A novel method with 3^{rd}, 5^{th}, and 7^{th} harmonic injection in sine-triangle modulation was proposed in [2]. However, the relationship between SVM and sine-triangle modulation is not well understood especially in multilevel multi-phase systems. Firstly, this paper presents the details of each method implemented in MATLAB/Simulink. Then, the relationship harmonic injection schemes and SVM is shown. Simulation test of the results are used to validate the proposed idea.

2. Three-Level Five-Phase IM Motor Drive System Description

Parameters	Number
DC voltage	900V
Switching frequency	10000Hz
Pole	4
Rs	1.26 Ω
Rr	1.03 Ω
Ls	0.00476H
Lr	0.0017H
Lm	0.37875H
J	0.015Kgm^2
Bm	0.0015Nms
Tl	0

Table 1. The parameters of IM motor

2.1 Three-Level Five-Phase Inverter Topology

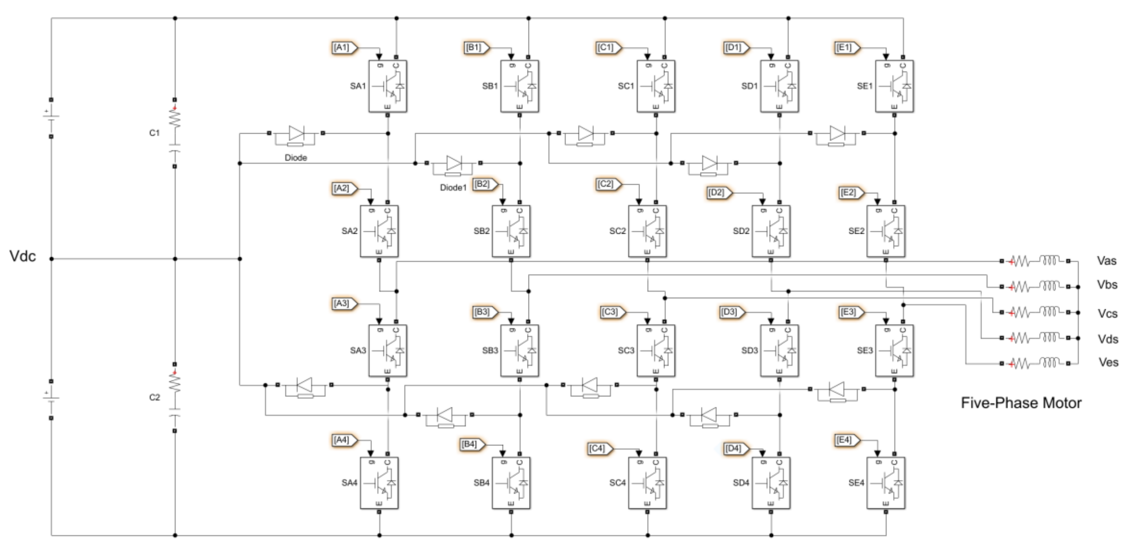

Figure 1. The scheme of three-level five-phase VSI

Figure 1 shows a typical of three-level five-phase IGBT inverter composed by five phase legs with four transistors each. Twenty switches (SA1~SA4, SB1~SB4, SC1~SC4, SD1~SD4) were controlled by the switching signal. The analyzed load in this paper is an induction motor with sinusoidal distributed windings. Thus, the goal is to create sinusoidal output phase voltages.

2.2 Arbitrary reference frame transformation (Clarke's transformation matrix)

$$\begin{bmatrix} V_{q1} \\ V_{d1} \\ V_{q3} \\ V_{d3} \\ V_0 \end{bmatrix} = \frac{2}{5} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{5}) & \cos(\theta - \frac{4\pi}{5}) & \cos(\theta + \frac{4\pi}{5}) & \cos(\theta + \frac{2\pi}{5}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{5}) & \sin(\theta - \frac{4\pi}{5}) & \sin(\theta + \frac{4\pi}{5}) & \sin(\theta + \frac{2\pi}{5}) \\ \cos(\theta) & \cos(\theta + \frac{4\pi}{5}) & \cos(\theta - \frac{2\pi}{5}) & \cos(\theta + \frac{2\pi}{5}) & \cos(\theta - \frac{4\pi}{5}) \\ \sin(\theta) & \sin(\theta + \frac{4\pi}{5}) & \sin(\theta - \frac{2\pi}{5}) & \sin(\theta + \frac{2\pi}{5}) & \sin(\theta - \frac{4\pi}{5}) \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_{q1} \\ V_{q1} \\ V_{q1} \\ V_{q1} \\ V_{q1} \end{bmatrix} \quad (1)$$

In this case variables such as voltage, current, or flux linkage are in an 72º five-phase unsymmetrical coordinate system. By using the Clarke's transformer, variables were transformed into d_1-q_1, and d_3-q_3 orthogonal coordinate systems.

2.3 Model of Three-level Five-Phase Induction Motor

Stator circuit equations:

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_e \psi_{qs} \quad (2)$$

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega_e \psi_{ds} \quad (3)$$

Rotor circuit equations:

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_r)\psi_{qr} \quad (4)$$

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \quad (5)$$

Flux linkage expressions in terms of the currents:

$$\psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \quad (6)$$

$$\psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \tag{7}$$

$$\psi_{qs} = L_{ls} i_{ds} + L_m (i_{qs} + i_{qr}) \tag{8}$$

$$\psi_{qr} = L_{lr} i_{dr} + L_m (i_{qs} + i_{qr}) \tag{9}$$

Torque equation:

$$T_e = P L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \tag{10}$$

$$\omega_r = \int \frac{P}{2J} (T_e - T_L) dt \tag{11}$$

Substitute the variables in d1-q1 and d3-q3 into the induction motor equations above. Model equations (2-9) show the reference stator voltage and rotor voltage controlled by flux linkage. And (10-11) show the relationships between torque and other variables. Where Lm=(n/2) M and M is the maximum value of the stator to rotor mutual inductances in the phase-variable model [3].

The mathematical equations presented above are used to model the three-level five-phase induction motor in MATLAB/Simulink. Measure the phase voltages (Vas~Ves) in the five-phase motor drive system. And the inputs of the induction model Vds1, Vqs1, Vds3, and Vqs3 can get from transformation matrix (1). In Figure 2 the five-phase induction motor equivalent circuits built up by MATLAB/Simulink is shown.

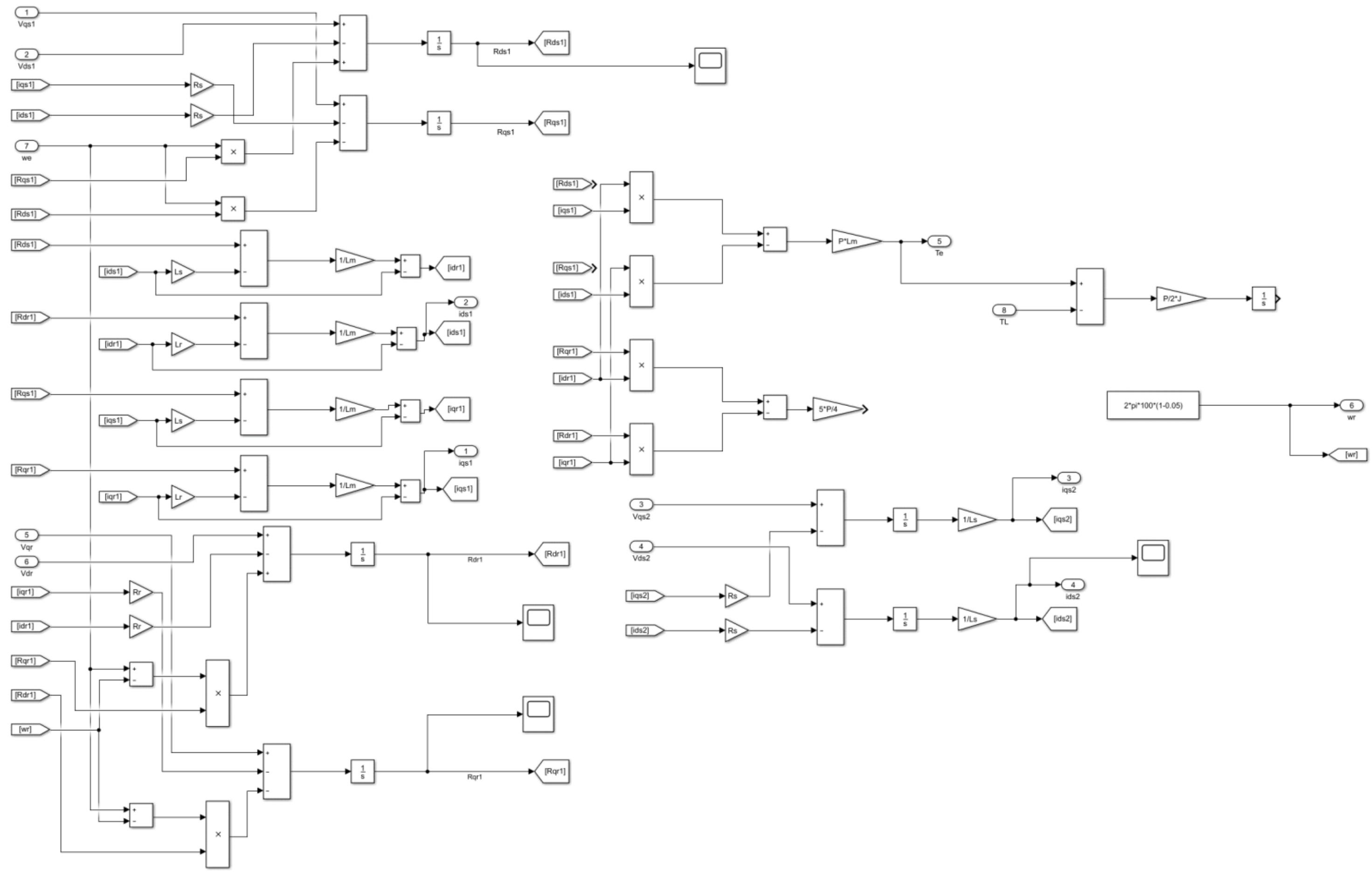

Figure 2. The model of five-phase IM

3. Space-Vector Modulation

Space-vector PWM (SVPWM) method were widely used in Multilevel Multiphase VSI due to the convince control of switching sequences. Firstly, the dwell time of switches can be decided easily and quickly in a control cycle. Secondly, the output voltage should be optimized by switching sequences to satisfy some specific requirements such as decreasing the switching loss and reducing the harmonics [13]. In this paper, two three-level five-phase SVPWM methods were presented. The results were implemented by MATLAB/Simulink.

3.1 SVPWM Basic Theory

The topology of three-level five-phase VSI is shown in Figure 1. The switching function can be defined as S= [Sa, Sb, Sc, Sd, Se]. If Sa=2, SA1 and SA2 will switch on; If Sa=1, SA2 and SA3 will switch on; If Sa=0, A3 and A4 will switch on. Thus, the five phase voltages can be expressed as follow format [4]:

$$V_{as} = \frac{S_a - 1}{2} V_{dc} \tag{12}$$

$$V_{bs} = \frac{S_b - 1}{2} V_{dc} \tag{13}$$

$$V_{cs} = \frac{S_c - 1}{2} V_{dc} \tag{14}$$

$$V_{ds} = \frac{S_d - 1}{2} V_{dc} \tag{15}$$

$$V_{es} = \frac{S_e - 1}{2} V_{dc} \tag{16}$$

And the space voltage vector is defined:

$$V_o = \frac{1}{5} V_{dc} (S_a + S_b e^{\frac{2}{5}\pi} + S_c e^{\frac{4}{5}\pi} + S_d e^{\frac{6}{5}\pi} + S_e e^{\frac{8}{5}\pi}) \tag{17}$$

A five-phase machine can be modelled in two 2D sub-space V_{ds1}-V_{qs1} and V_{ds3}-V_{qs3} based on the decomposition method (18) (19). The reference voltage should be considered pure sinusoidal in V_{ds1}-V_{qs1} while null in the V_{ds3}-V_{qs3}. If not, the current will be distorted by voltage in V_{ds3}-V_{qs3} plane [14-16].

$V_{qs1-ds1} = \frac{2}{5}(V_{as} + V_{bs}e^{\frac{2}{5}\pi} + V_{cs}e^{\frac{4}{5}\pi} + V_{ds}e^{\frac{6}{5}\pi} + V_{es}e^{\frac{8}{5}\pi})$	(18)
$V_{qs3-ds3} = \frac{1}{5}(V_{as} + V_{cs}e^{\frac{2}{5}\pi} + V_{es}e^{\frac{4}{5}\pi} + V_{bs}e^{\frac{6}{5}\pi} + V_{ds}e^{\frac{8}{5}\pi})$	(19)

In this case, each phase can have three possible outputs (S=2, 1, or 0) hence there are 243voltage vectors in a decagon divided by ten 36º sectors. However, not all these vectors are useful. Some of vectors should be eliminated. Because V_{ds3}-V_{qs3} vector space voltage represents a distortion voltage, it is necessary to make V_{ds3}-V_{qs3} vector null. After the eliminating, only 113 space vector remain from the original 243 [1]. The V_{ds1}-V_{qs1} plot is shown in Figure 3. And the magnitude of the vertex voltage vectors in each decagon can be calculated: 0.2V_{dc}, 0.324 V_{dc}, 0.4 V_{dc}, 0.524 V_{dc}, 0.647 V_{dc}.

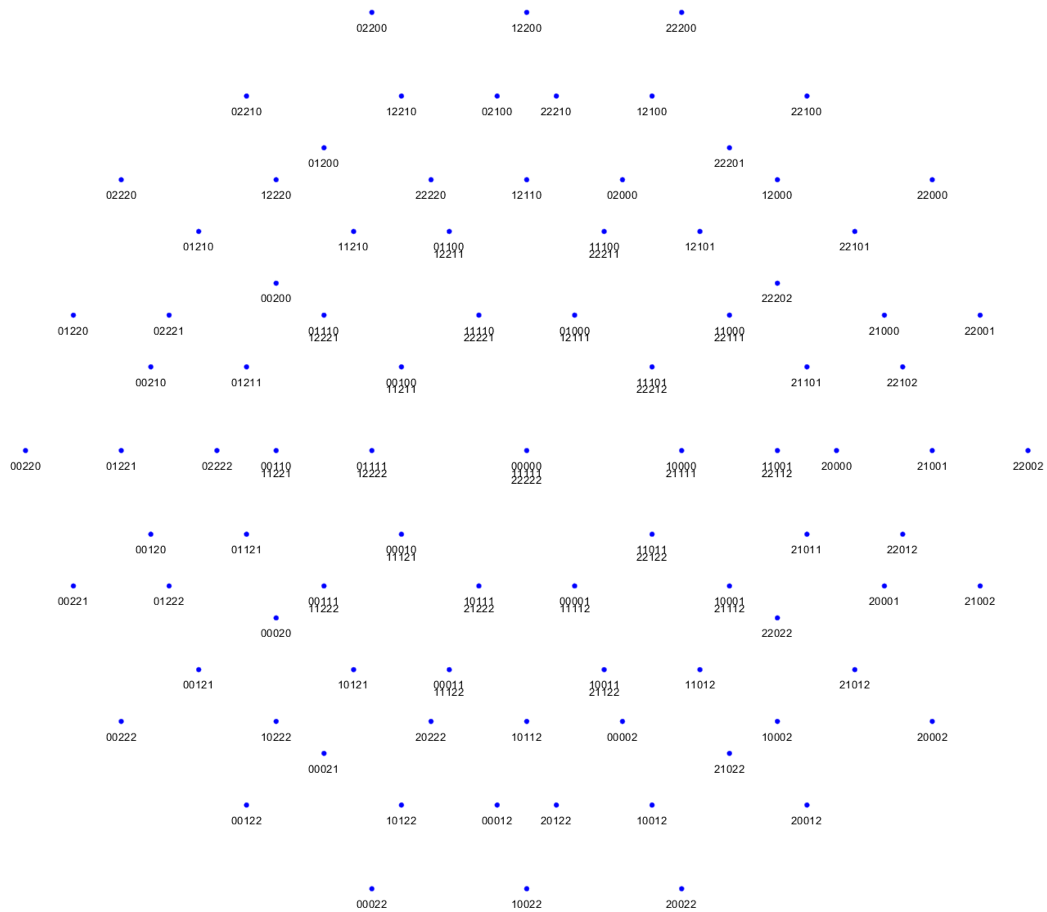

Figure 3. Vds1-Vqs1 space vector plot

Design the dwell time and region partition algorithm, then chose the switching sequences in Figure 3. Here gives a method of dwell time calculation model design.

The five-phase system is different from the three-phase system as it is necessary to eliminate the distortion caused by V_{ds3}-V_{qs3}. Normally in the five-phase system, five space vectors were used in each switching sequence hence the V_{ds3}-V_{qs3} component can be canceled [1]. The relationships between resultant space vectors and dwell time were shown by following equations:

$T_s \vec{V}_{dq1ref} = T_0 \vec{V}_0 + T_1 \vec{V}_1 + T_2 \vec{V}_2 + T_3 \vec{V}_3 + T_4 \vec{V}_4$	(20)
$T_s \vec{V}_{dq3ref} = T_0 \vec{V}_0 + T_1 \vec{V}_1 + T_2 \vec{V}_2 + T_3 \vec{V}_3 + T_4 \vec{V}_4 = 0$	(21)
$T_s = T_0 + T_1 + T_2 + T_3 + T_4$	(22)

Where Ts is the switching period, and T_0 T_1 T_2 T_3 T_4 are the dwell time of each switching sequence vector.

3.2 Details of Implementation In MATLAB/Simulink

3.2.1 Simulink Models

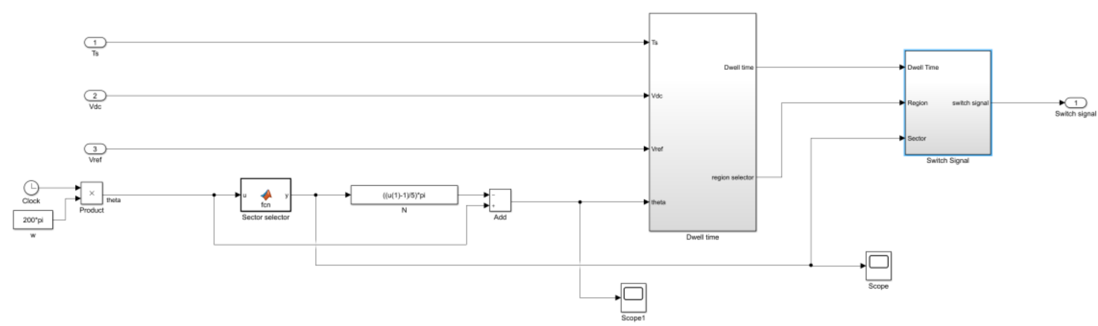

Figure 4. Switching signal trigger block

There are three main parts in the Simulink circuit: Three-level five-phase VSI (Figure 1), Switching signal trigger (Figure 4), and IM model (Figure 2). In this part, it mainly introduces the details of the second part.

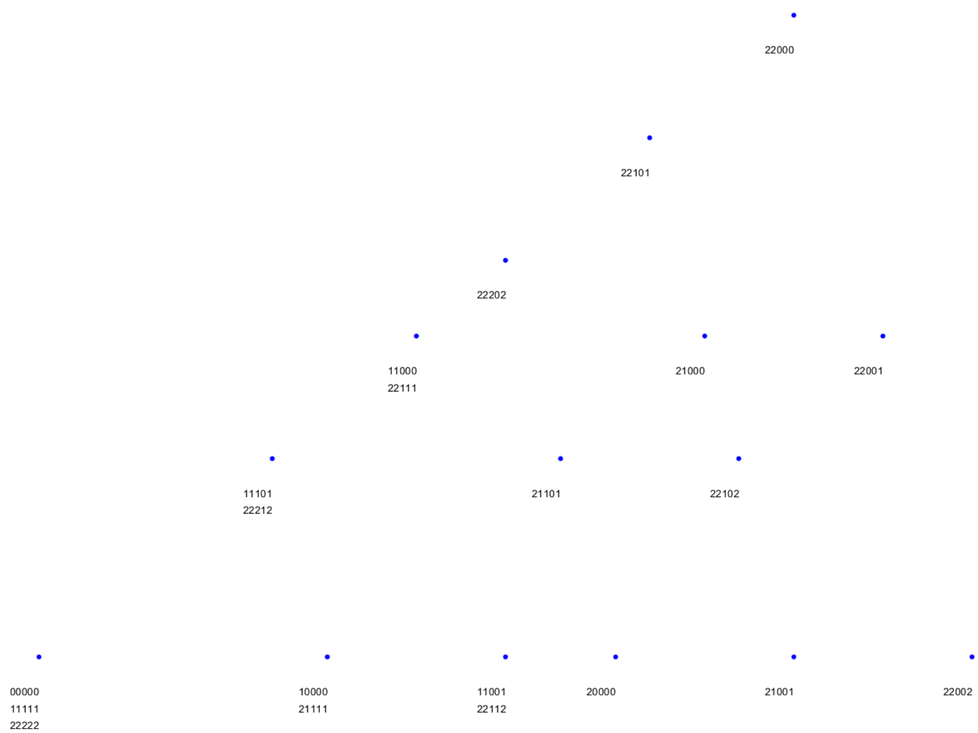

Figure 5. Vds1-Vqs1 space vector sector 1

Although there are ten sectors in the space vector plot, researchers can only take the first sector into consideration due to the order of each sequences would be the same as it goes in sector1shown in Figure 5. Firstly, transfer all situations into sector1 to do the next calculations. In Figure 4, the formulation in the Sector selector block is y=1+fix(mod(u,2*pi)/(pi/5)). And then input the transferred theta angel into the dwell time calculator shown in Figure 6.

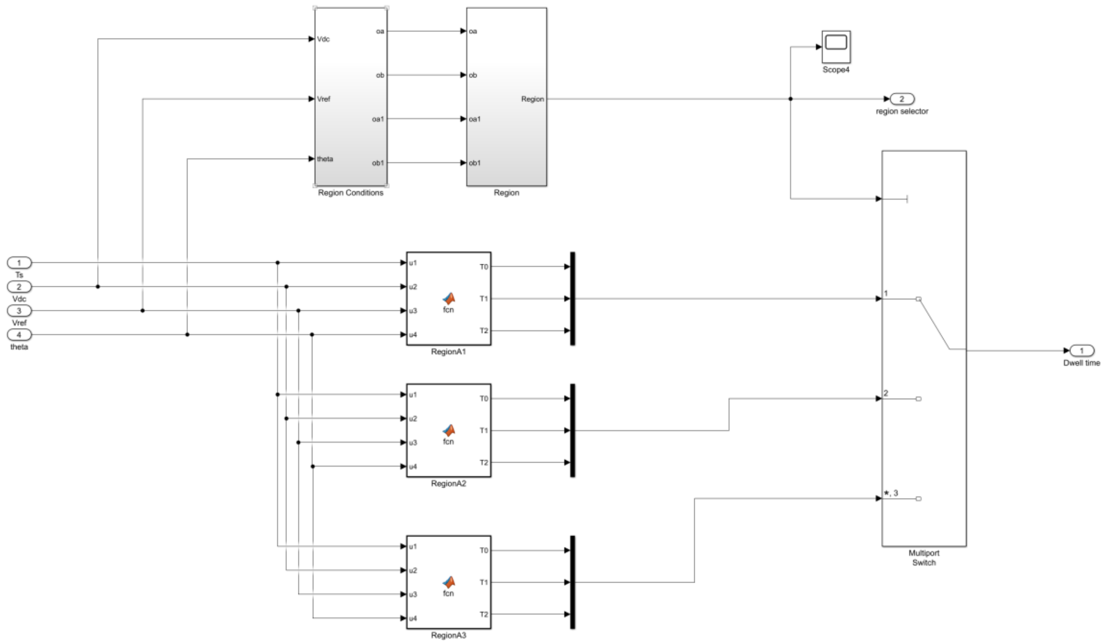

Figure 6. Dwell time calculator (Nearest three vectors SVPWM)

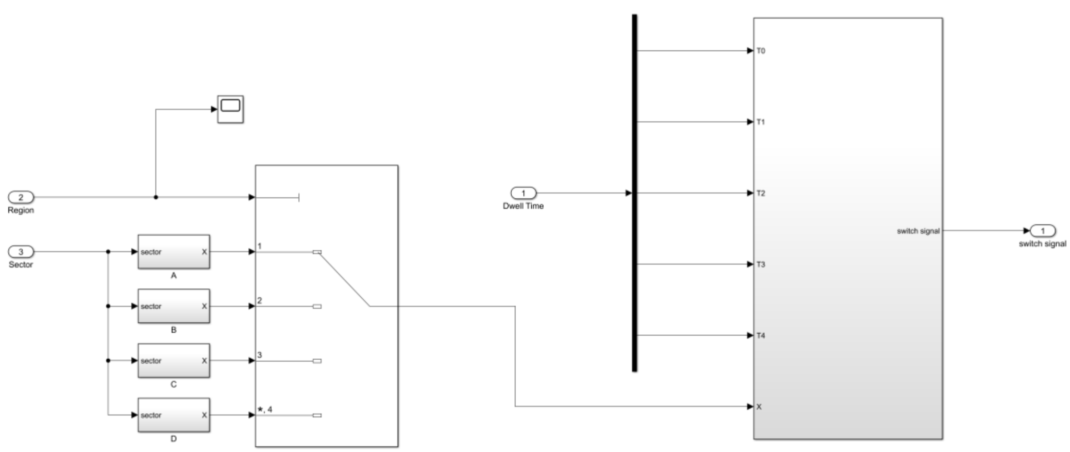

Figure 7. Switching signal trigger block (Nearest three vectors SVPWM)

Generally, researchers prefer to divide the sector 1 into some special regions to implement the functions. So, the region selectors become the most important part to design the dwell time calculator. In this paper, two different algorithms were presented.

One is using nearest three vectors, and another is using optimized switching sequences SVPWM with five switching sequences.

3.2.2 Using Nearest three vectors SVPWM

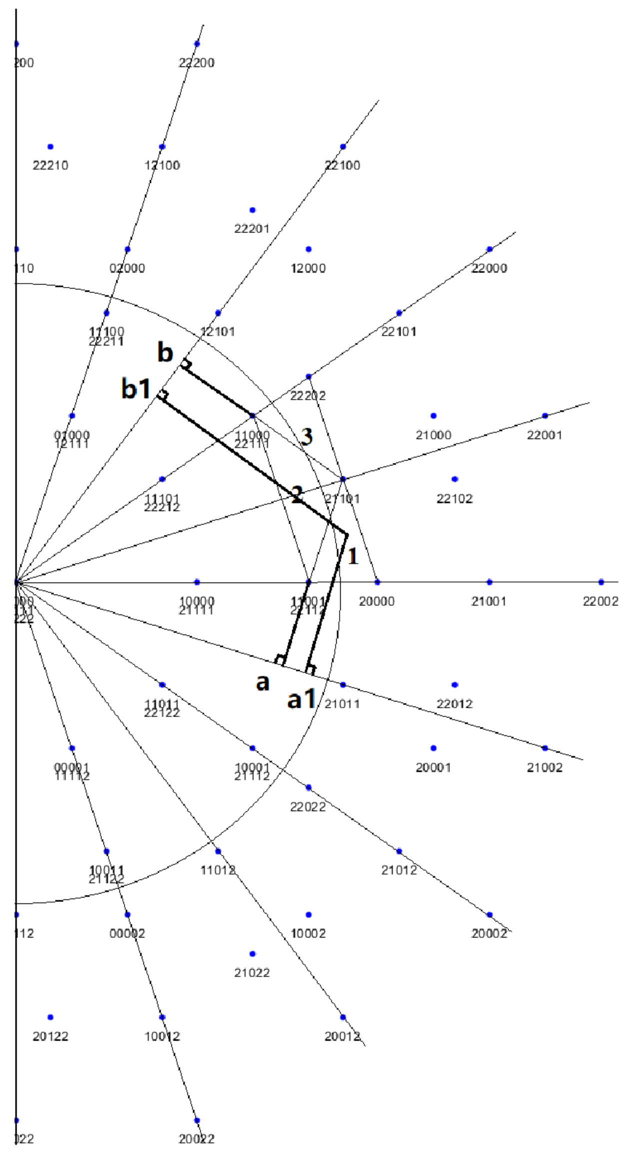

Figure 8. Switching sequences selector and region determination with low modulation index

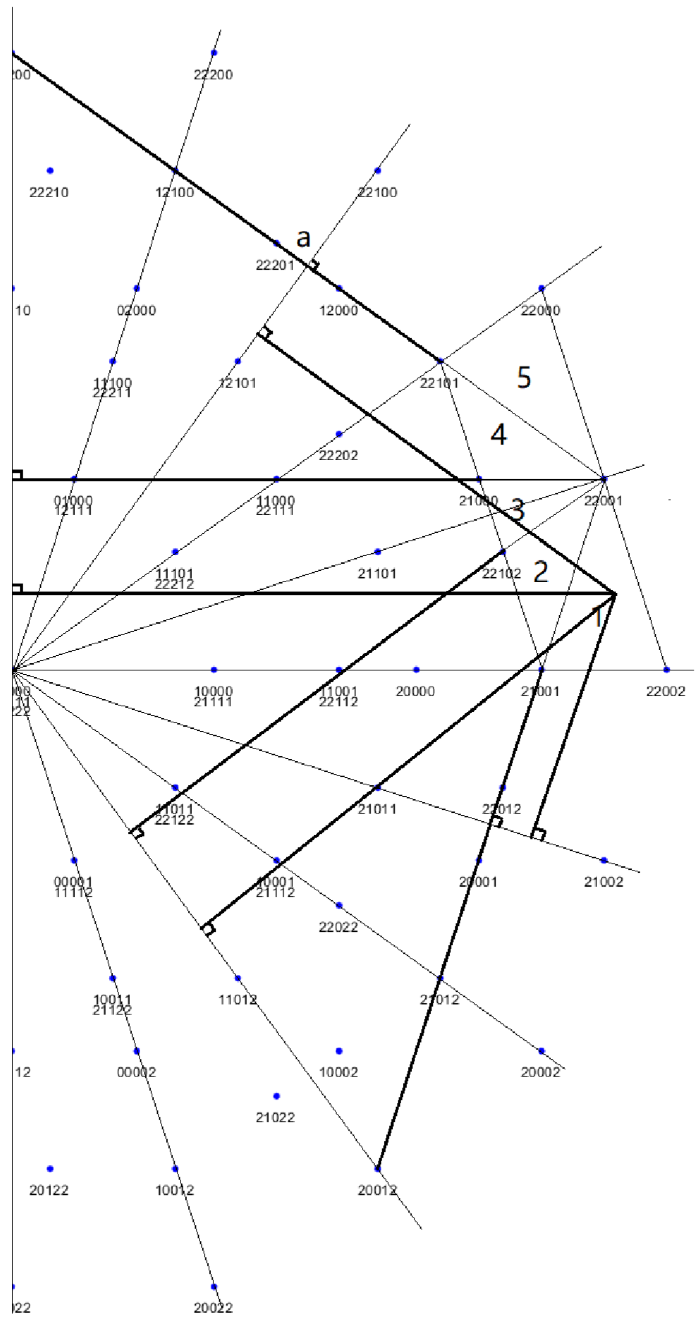

Figure 9. Switching sequences selector and region determination with high modulation index

Figure 8, and 9 show the inverter states and the region determination algorithm in the first sector by using different modulation index. For example, the first sector was divided into 3 regions in Figure 8. Switching sequence 1 has a sequence 21101-11001-20000 in region 1; Switching sequence 2 has a sequence 21101-11001-11000 in region.2; Switching sequence 3 has a sequence 21101-11000-22202 in region 3. The number of the region should be decided when reference voltage goes through the first region Thus, a simple method of determining the location of the reference voltage has been developed. Each region is a triangular which is determined by three distinctive sides. And these sides are perpendicular to the centerlines of adjacent and nonadjacent sectors. Hence, some line segments are shown in Figure 8 and 9. Using the length of these line segment “oa”, “ob”, “oc” and “od” can determine the accessible region when the reference sweeps different regions in the first sector. Table 1 and Table 2 summarize the expressions of the segment length and the region determination algorithm in both low and high modulation index situations. Finally, the switching signal can be generated if the switching sequences were input into the matrix. Mention that using this method cannot eliminate the distortion caused by V_{ds3}-V_{qs3}.

Line length	Region conditions
$oa = 0.324\cos\frac{\pi}{10}$ $ob = 0.324\cos\frac{\pi}{10}$ $oa_1 = V_{ref}\cos(\frac{\pi}{10}+\theta)$ $ob_1 = V_{ref}\cos(\frac{3\pi}{10}-\theta)$	$1. oa_1 > oa$ $2. oa_1 \le oa$ $3. ob_1 < ob; ob_1 \ge ob$

Table 1. Region determination in Sector1 with low modulation index

Line length	Region conditions
$oa = 0.524V_{dc}\cos\frac{\pi}{10}$ $ob = 0.524V_{dc}\cos\frac{\pi}{10}$ $oc = 0.324V_{dc}\cos\frac{3\pi}{10}$ $od = 0.2V_{dc}\cos\frac{3\pi}{10}$ $oa_1 = V_{ref}\cos(\frac{3\pi}{10}-\theta)$ $ob_1 = V_{ref}\cos(\frac{\pi}{10}+\theta)$ $oc_1 = V_{ref}\cos(\frac{\pi}{2}-\theta)$ $od_1 = V_{ref}\cos(\frac{3\pi}{10}+\theta)$	$1. ob_1 \ge ob$ $2. ob_1 < ob; od_1 \ge od$ $3. od_1 < od; oc_1 \le oc$ $4. oc_1 > oc; oa_1 \le oa$ $5. oa_1 > oa$

Table 2. Region determination in Sector1 with high modulation index

3.2.3 Using optimized switching sequences SVPWM

A novel algorithm for three-level five phase SVPWM is developed in [1]. This method should follow three requirements to optimize the switching sequences:

1. Five vectors modulation instead of three vectors modulation in the nearest three method was used to optimize the switching sequences.
2. Select the switching sequences which could eliminate the combination of vectors in V_{ds3}-V_{qs3}.
3. The inverter can only make one transition during one switching state to minimize the switching loss.

Select the proper switching sequences based on the rules above. The possible switching sequences are shown in Table 3. Then decide the possible regions formulated by these ten switching sequences and design the determination algorithm of reference voltage location. The method would be the same as using nearest three vectors SVPWM.

Number	Proper switching sequences
1	11001-11101-11111-21111-22111
2	11001-11101-21101-21111-22111
3	11001-21001-21101-21111-22111
4	11001-21001-21101-22101-22111
5	11001-11101-21101-22101-22111
6	11001-21001-22001-22002-22102
7	11001-21001-22001-22101-22102
8	11001-21001-22001-22101-22111
9	11000-21000-21001-22001-22101
10	11000-21000-22000-22001-22101

Table 3. Optimized switching sequences in sector1

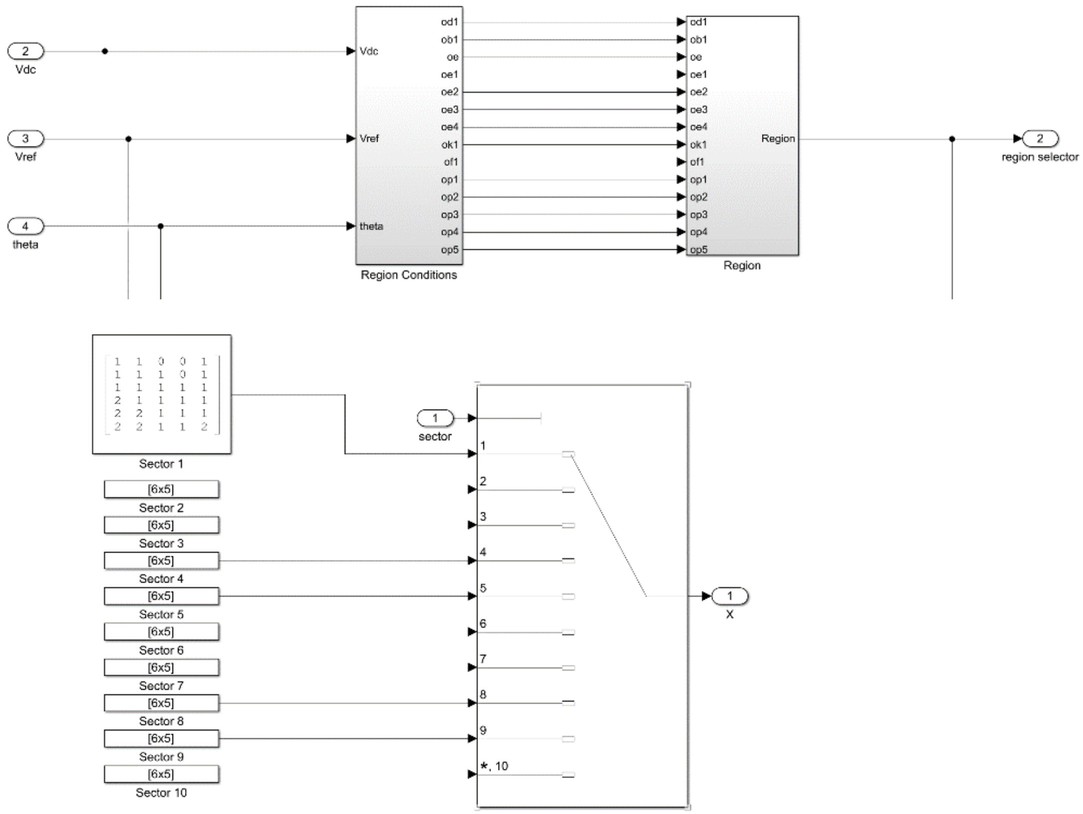

Figure 10. Implementation of optimized switching sequences by using MATLAB/Simulink

3.3 Simulation Results

Simulation is done by using MATLAB/Simulation version 2017b to show the results of three-level five- phase VSI. Five phase supply is given to a five-phase induction motor under no load condition. Motor behavior is observed especially the torque ripple.

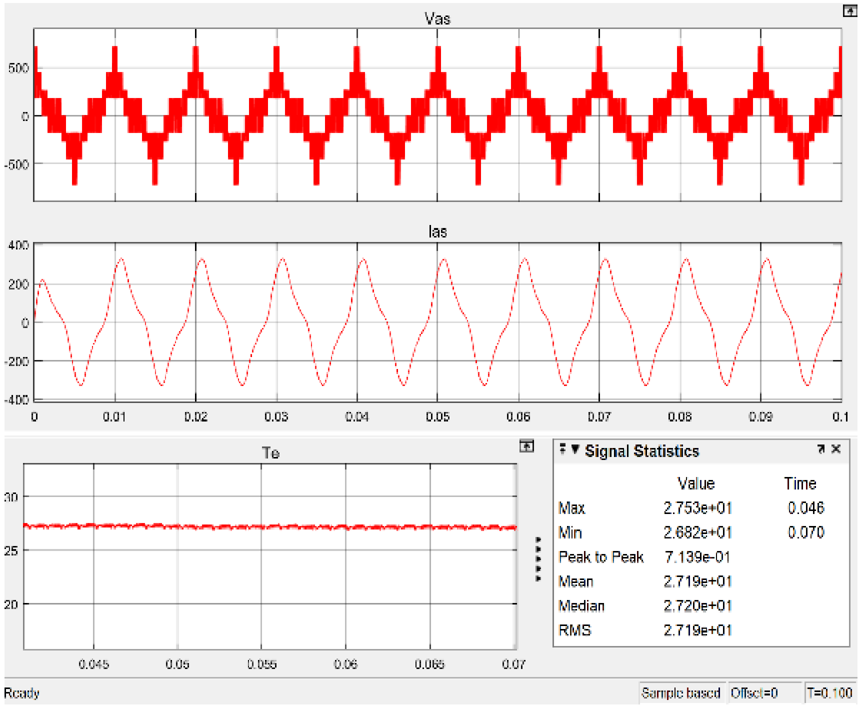

Figure 11. Simulated motor phase voltage, current and torque by using nearest three vectors with low m

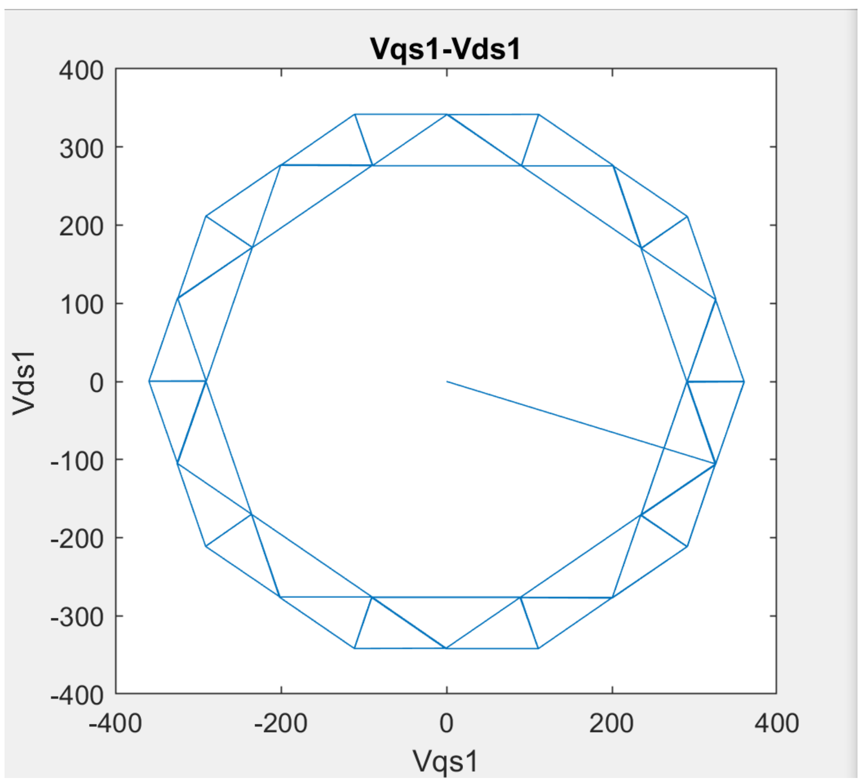

Figure 12. Vds1-Vqs1 plot by using nearest three vectors with low m

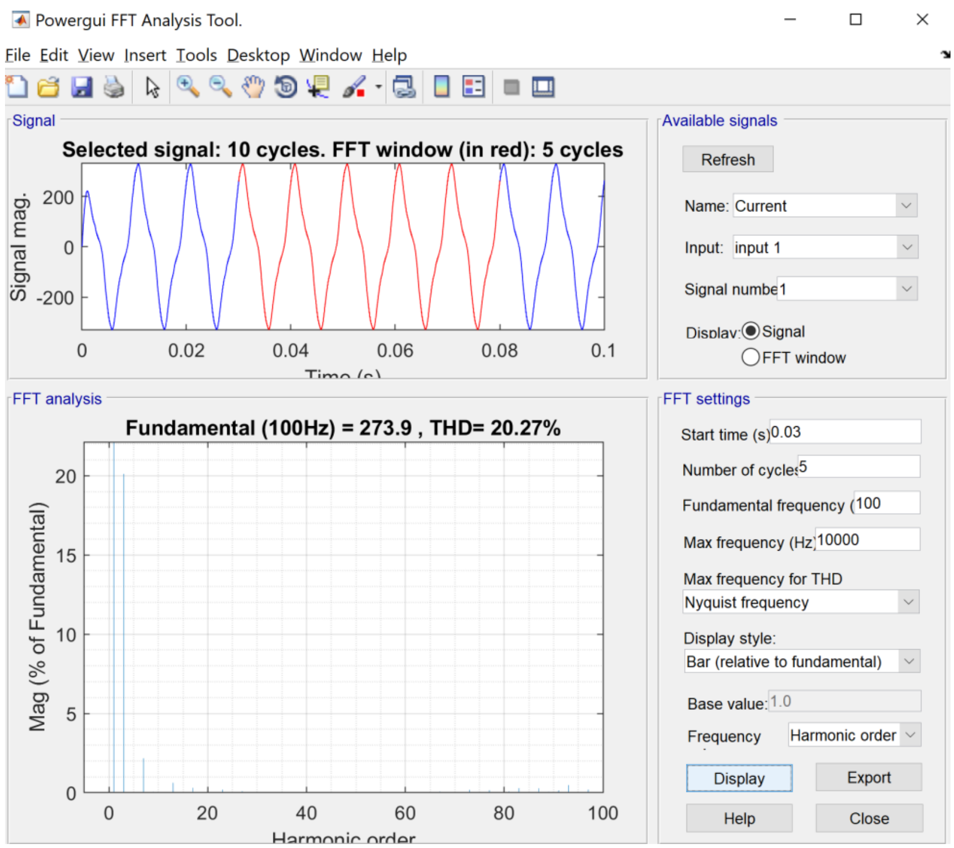

Figure 13 FFT analysis by using nearest three vectors with low m

Figure 11 shows phase voltage, phase current and the torque of the five-phase machine when m=0.36 by using nearest three vectors method. The reference voltage path is the situation in Figure 8, and the simulated result shows the switching sequences path in Figure 12. The dc supply voltage was 900V and the switching frequency was 10000Hz. The value of phase voltage is 323.4V peak (228.7V RMS) and phase current is 273.9A peak (193.6A RMS). The torque ripple in the example is 2.6%. Mention that in this case, because this method cannot make V_{ds3}-V_{qs3} to be null, there is some distortion in the phase current. Figure 13 shows the FFT analysis of phase current in Simulink/Powergui.

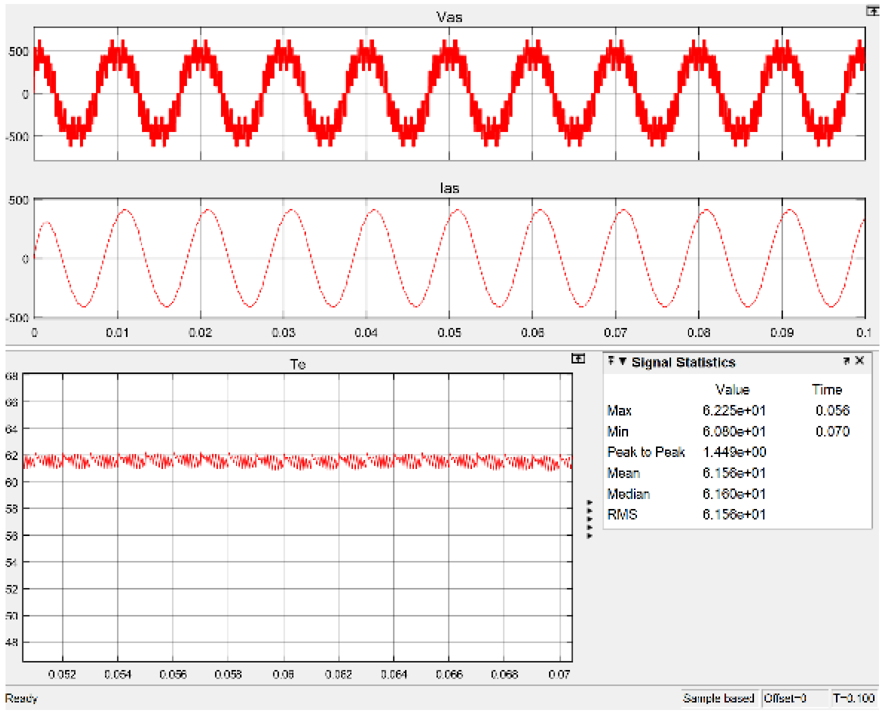

Figure 14. Simulated motor phase voltage, current and torque by using nearest three vectors with high m

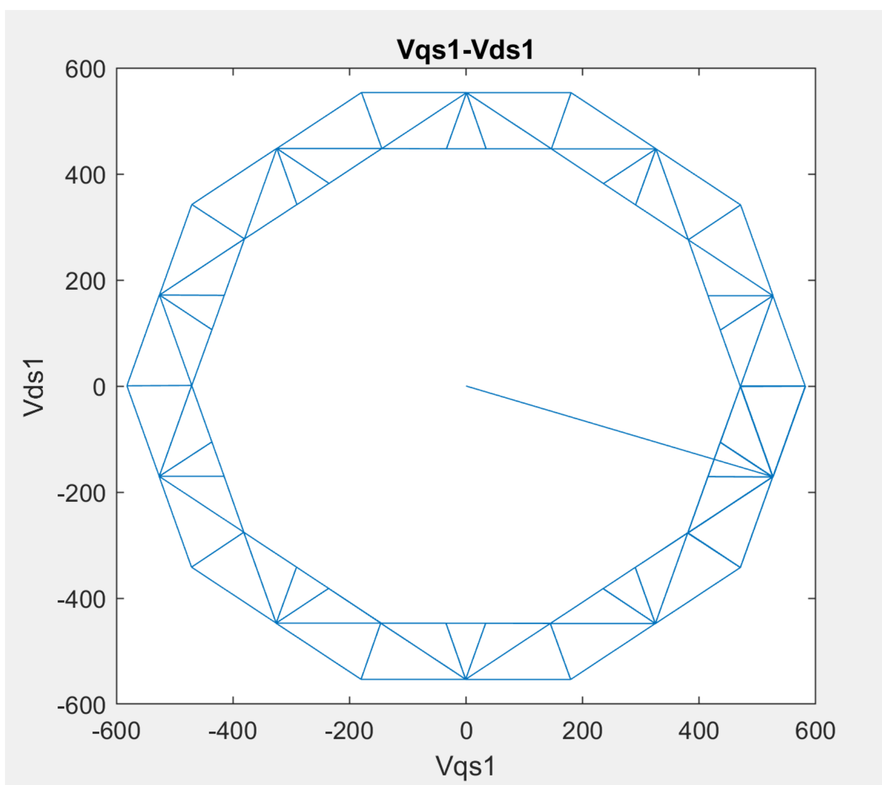

Figure 15. Vds1-Vqs1 plot by using nearest three vectors with high m

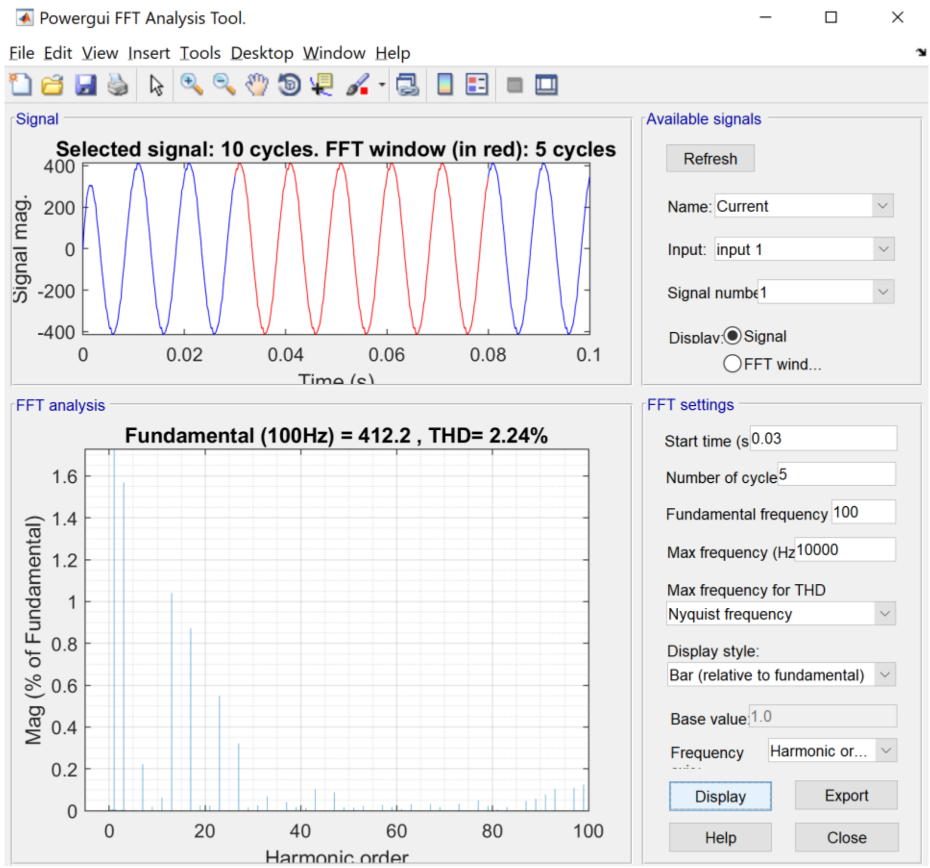

Figure 16 FFT analysis by using nearest three vectors with high m

Figure 14 shows phase voltage, phase current and the torque of the five-phase machine when m=0.54 by using nearest three vectors method. The reference voltage path is the situation in Figure 9, and the simulated result shows the switching sequences path in Figure 15. The dc supply voltage was 900V and the switching frequency was 10000Hz. The value of phase voltage is 486.9V peak (344.3V RMS) and phase current is 412.2A peak (291.5A RMS). The torque ripple in the example is 2.36%. Figure 16 shows the FFT analysis of phase current in Simulink/Powergui. In this case, there is also some distortion in the phase current waveform.

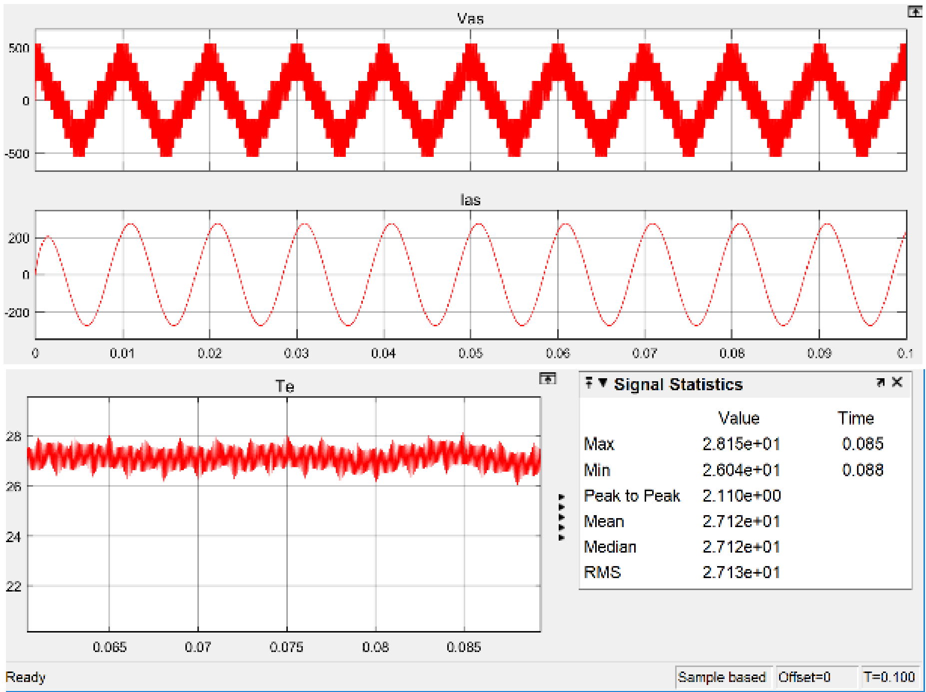

Figure 17. Simulated motor phase voltage, current and torque by using optimized method with low m

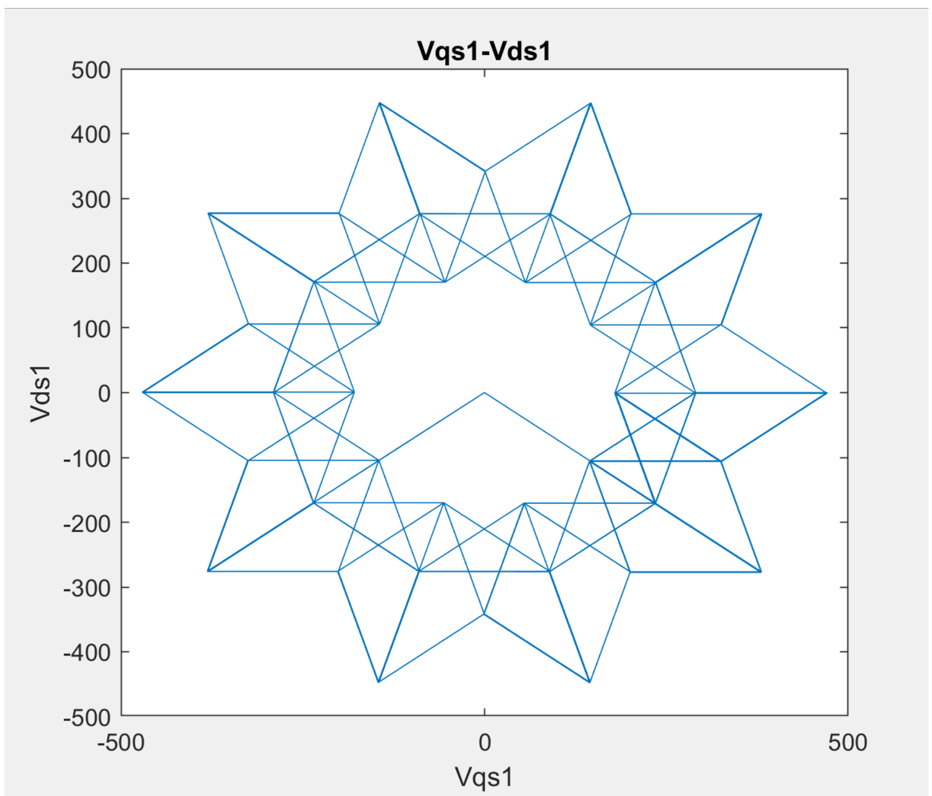

Figure 18. Vds1-Vqs1 plot by using optimized method with low m

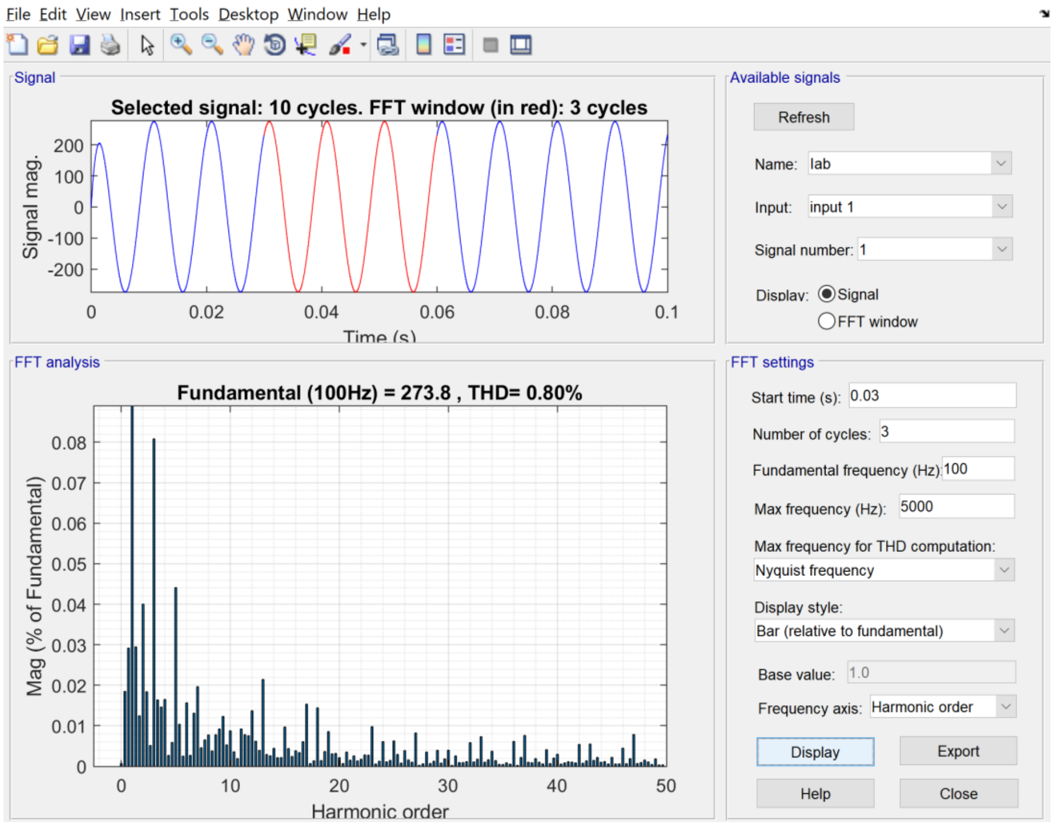

Figure 19 FFT analysis by using optimized method with low m

Figure 17 shows phase voltage, phase current and the torque of the five-phase machine when m=0.36 by using optimized method. The reference voltage path is the situation in Figure 9, and the simulated result shows the switching sequences path in Table 3. In this case, number 1 to 4 switching sequences are used in the example. The dc supply voltage was 900V and the switching frequency was 10000Hz. The value of phase voltage is 323.4V peak (228.7V RMS) and phase current is 273.8A peak (193.6A RMS). The torque ripple in the example is 7.74%. Here the torque ripple is lager than the case by using nearest three vectors method. Because the torque ripple can be reduced by harmonics of phase current. Figure 16 shows the FFT analysis of phase current in Simulink/Powergui. From Figure 16, there is only 0.8% THD in phase current due to the elimination of V_{ds3}-V_{qs3} vector.

4 Sine-Triangle Modulation

Sine- triangle modulation is another traditional method which is also wildly used in practice. In this method, a reference copy of the desired sinusoidal waveform, the modulating wave, is compared to a much higher frequency triangular waveform, called the carrier wave. For multilevel VSI, more identically shaped but offset triangle waveforms are needed as carrier waveforms. Compared to SVPWM, sine-triangle method is more efficient and flexible [17-20].

4.1 Typical Method

In this paper, the model is a three-level five-phase VSI. Figure 17 shows the typical of a three-level sine-triangle modulator. Two triangle waveforms are compared with the sinewave which is decided by the reference voltage (Three-level model). The frequency of the carriers is the switching frequency, and the amplitude is 0.5 V_{dc}. Figure 18 is the simulation of the switching signals. The modulation index (m) is related to the reference voltage and the harmonic injection. The maximum modulation index is calculated from [2]:

$$0.6472V_{dc}\cos(\frac{\pi}{10}) = \frac{m_{\max}}{2}V_{dc} \qquad (23)$$

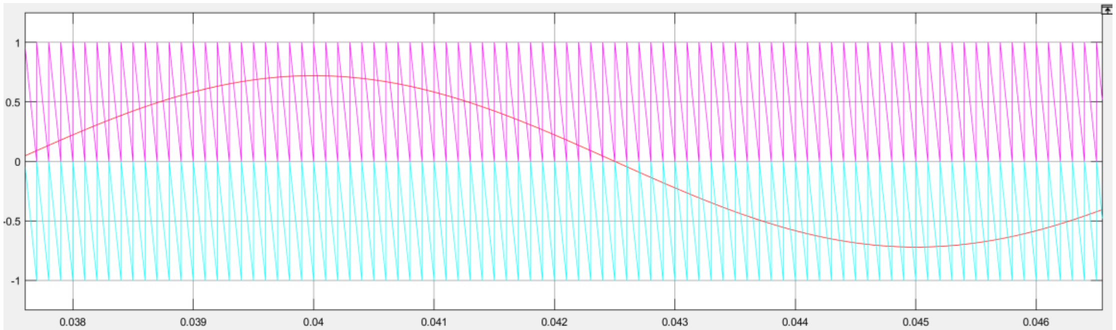

Figure 20. Three-level sine- triangle modulation

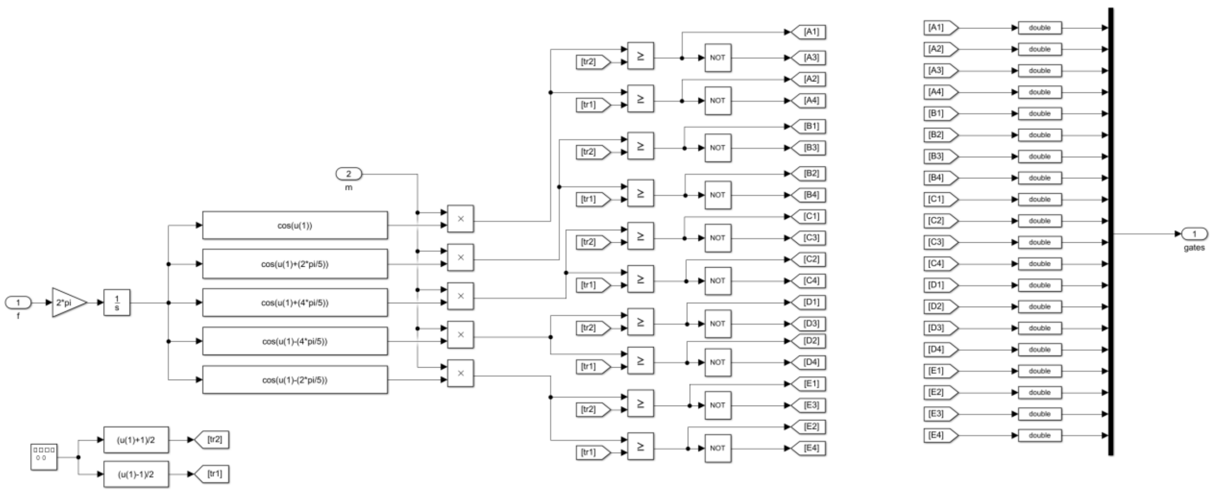

Figure 21. Three-level sine- triangle implementation in MATLAB/Simulink

In this case, the purpose is to compare the sine-triangle method with space vector method. Hence, the value of the modulation index should be twice as much as that of low modulation index(m=0.72) set in previous section. In this simulation, 58.5% of modulation index (calculated by formula (23)) was used in the example which represents the low m condition. The dc supply voltage was 900V. It created the 323V peak (228.4V RMS) fundamental phase voltage and 273.7A peak (193.5 RMS) fundamental phase current. Torque ripple in this case is 5.92%. The switching frequency was 10000Hz. Figure 19 and 20 are the simulated results.

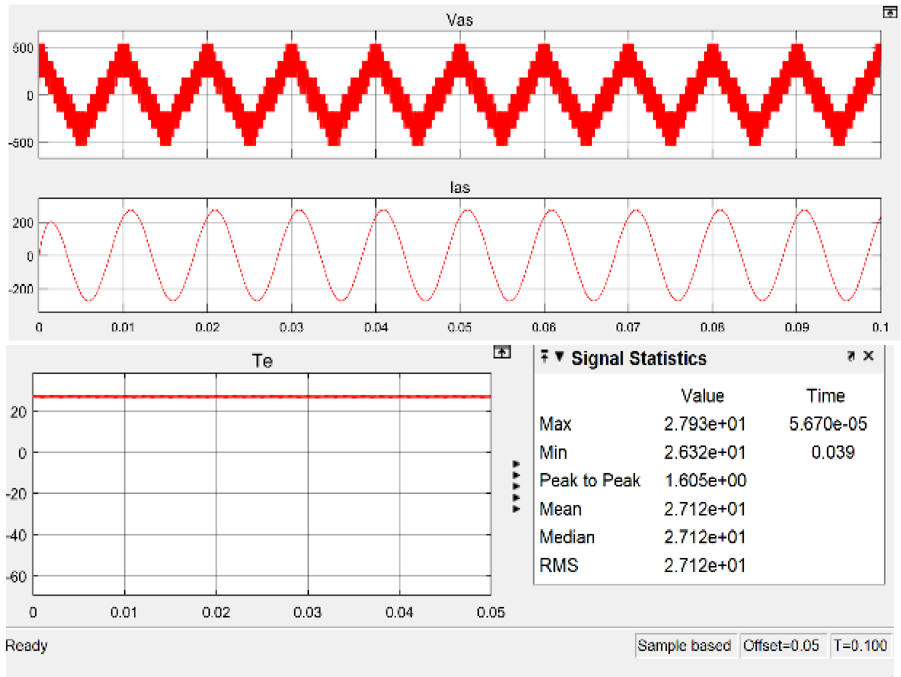

Figure 22 Simulated motor phase voltage, current and torque by using sine-triangle method with low m

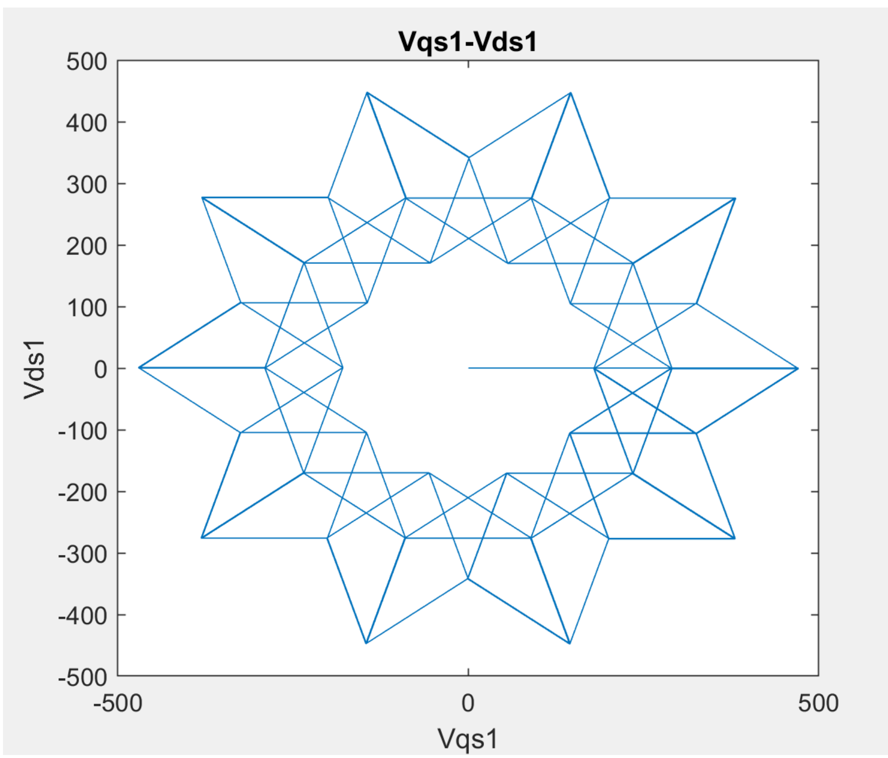

Figure 23 Vds1-Vqs1 plot by using sine-triangle method with low m

4.2 Adding harmonics by SVPWM

Add the harmonics to sine wave based on equation (24), the torque ripple can be improved. To determine the amount of harmonics that should be added into the system, testing every order of corresponding harmonic contents is a typical method. With 3^{rd}, 5^{th}, 7^{th}…harmonics injection, estimate the modulation index. And the m should be lower than the maximum modulation index, here is around 1.231 (calculated by (23)). Finally, researchers can get the optimal harmonic combination to improve the torque ripple.

$$V_g = \frac{V_{dc}}{2}[1 + m(\cos(\theta_e) + K_3 \cos(3\theta_e) + K_5 \cos(5\theta_e) + K_7 ...)] \quad (24)$$

In past research, it has been shown that SVPWM and carrier-based modulation methods are practically the same in the three-phase system. In the simulation of this part, the number of harmonic injection decided by the FFT result of nearest three vectors method (m=0.36). Figure 21 shows the FFT analysis result of phase voltage by using nearest three vectors method. From the list, K_3=36.34%, K_7=8.27%, and K_{13}=4.39%. Add these harmonics component into the system, the results of torque ripple (torque ripple=3.57%) which is improved than before are shown in Figure 22.

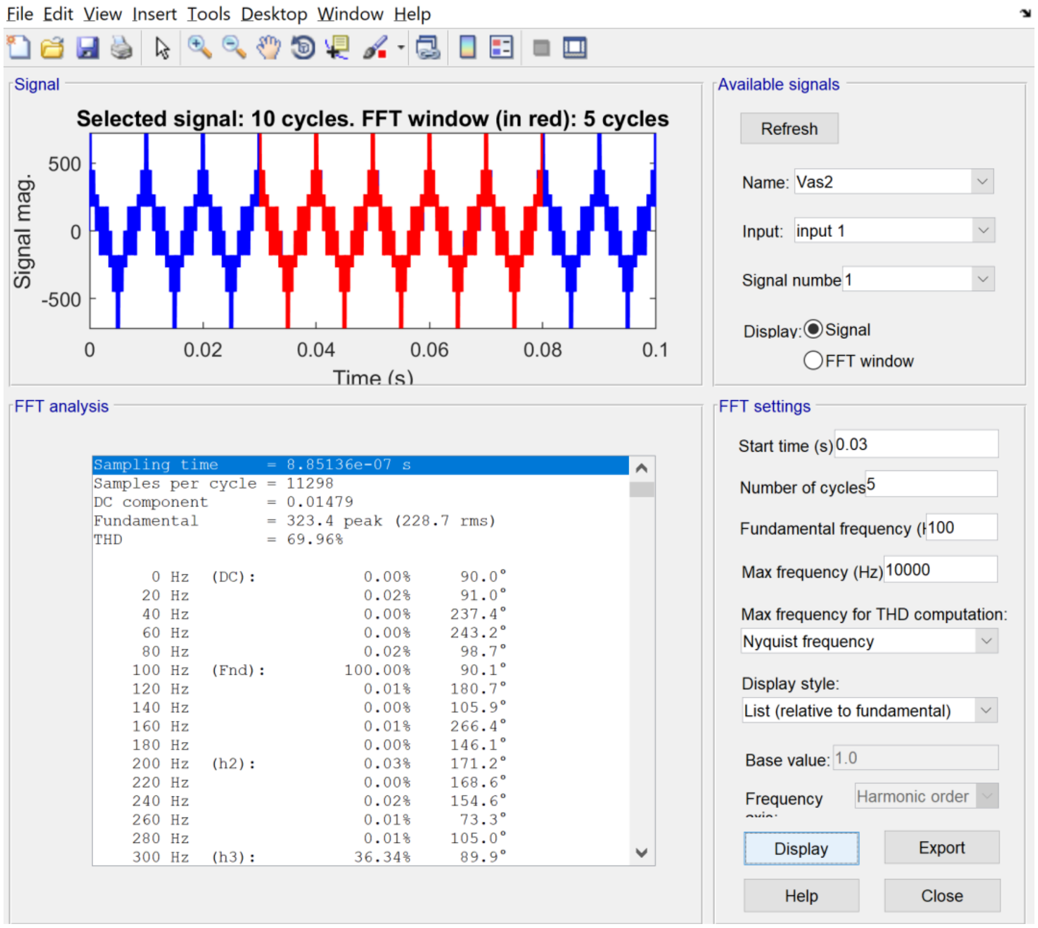

Figure 24 FFT analysis of phase voltage by using nearest three vectors method (m=0.36)

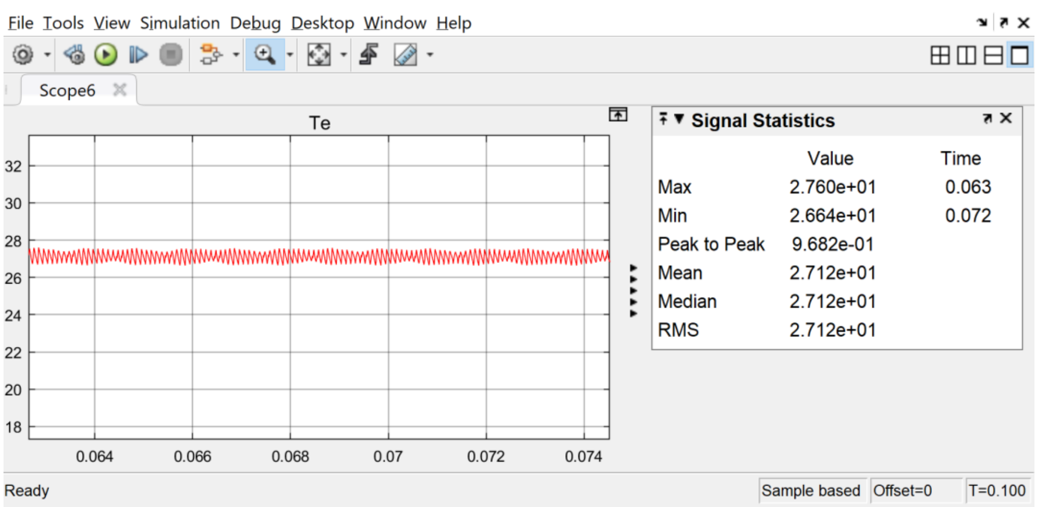

Figure 25 The result of torque after adding harmonics

4.3 Comparison to SVPWM

In the previous research, it is shown that sine-triangle method is more convenience and flexible than SVPWM. And this is the reason why people want to find a solution that can get the same torque performance by using sine-triangle modulation instead of SVPWM. However, they cannot be unified in the multi-level multi-phase system for some reasons.

Firstly, sine-triangle modulation is subject to the maximum modulation index when the harmonics were added into the system. For example, compared to nearest three vectors method m=0.54 (high m), the modulation should be fixed to 90% after adding harmonics. The vector sequences were nearly the same but cause some distortion of torque. From the Figure 23, torque ripple is 4.42% which is higher than using nearest three vectors method. And the Vds1-Vqs1 vector plot shows that the switching sequences cannot be the same as nearest three vectors method.

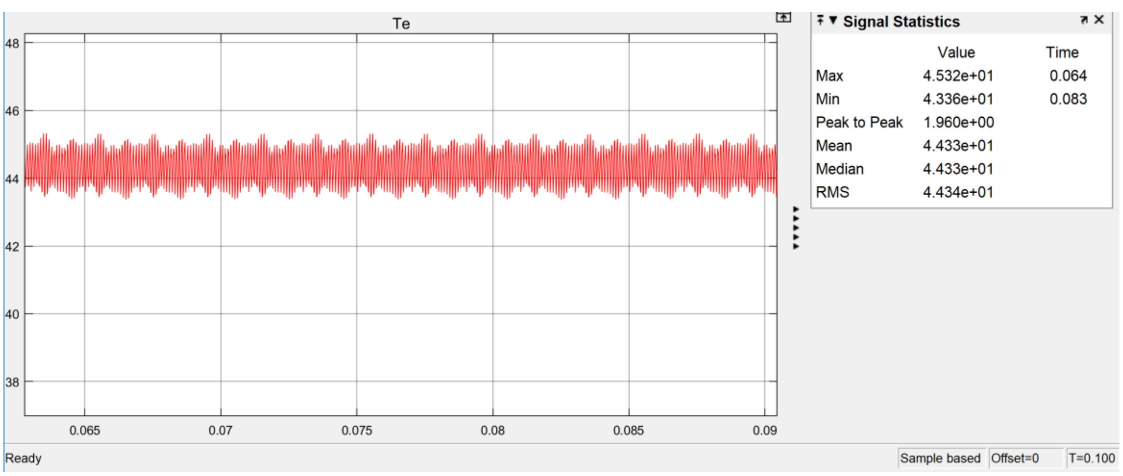

Figure 26 The result of torque after adding harmonics based on nearest three vectors method (m=0.54)

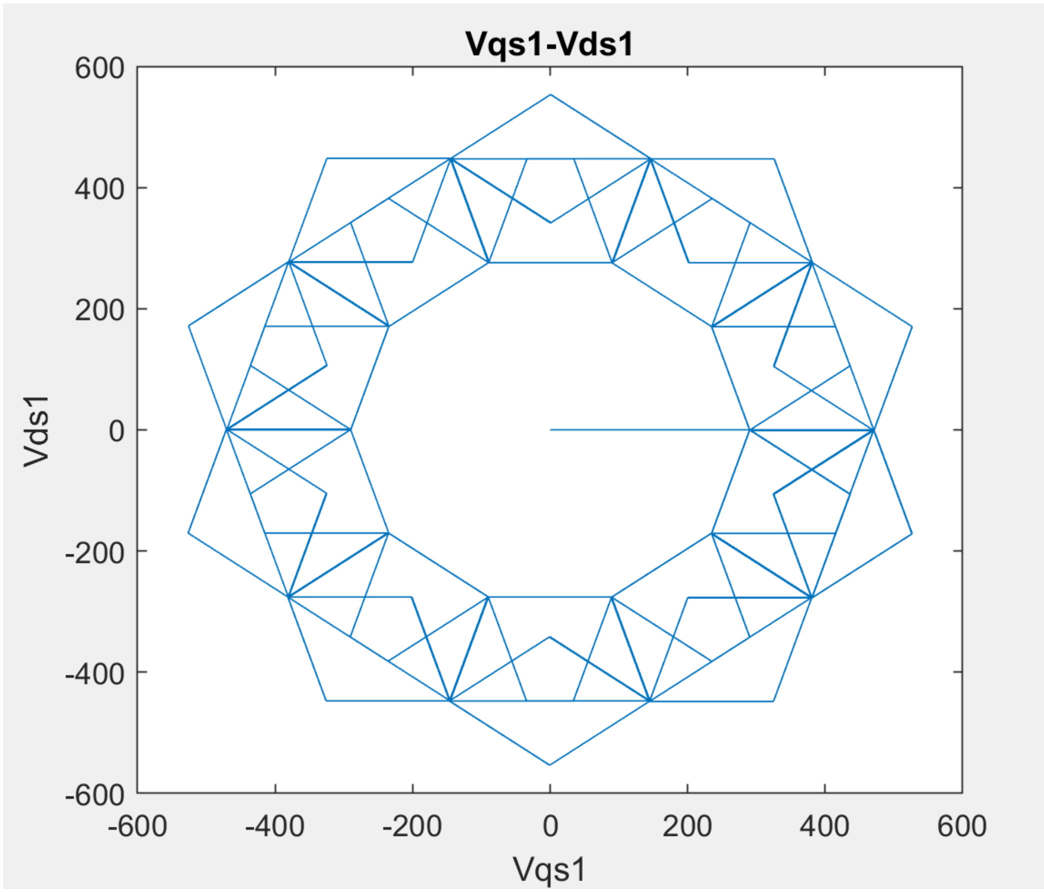

Figure 27 Vds1-Vqs1 plot of harmonics injection (m=0.54)

Secondly, in the sine-triangle modulation, the resulting drive signals cause multiple turn-on of the inverter switches in each half-cycle with variable pulse width to produce a quasi-sine wave of load voltage. It means that the switching sequences produced by this method must be continuous. In other words, sine-triangle wave modulation cannot design a random switching sequences. For example, in the nearest three vectors method with low m (m=0.36), the switching sequences in the original plot is not continuous. Thus, sine-triangle wave modulation is impossible to be the same switching sequences path by adding harmonics. Torque ripple is 3.49% in this case. Figure 25 and 26 show the simulation results. Mention that, in the three-phase system, the path of switching sequences could be the same because the switching sate are adjacent, and the switching sequences are always continuous.

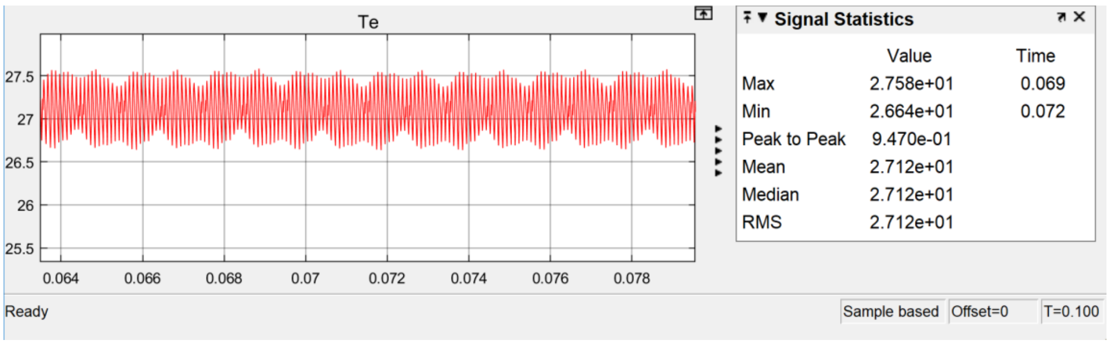

Figure 28 The result of torque after adding harmonics based on nearest three vectors method (m=0.36)

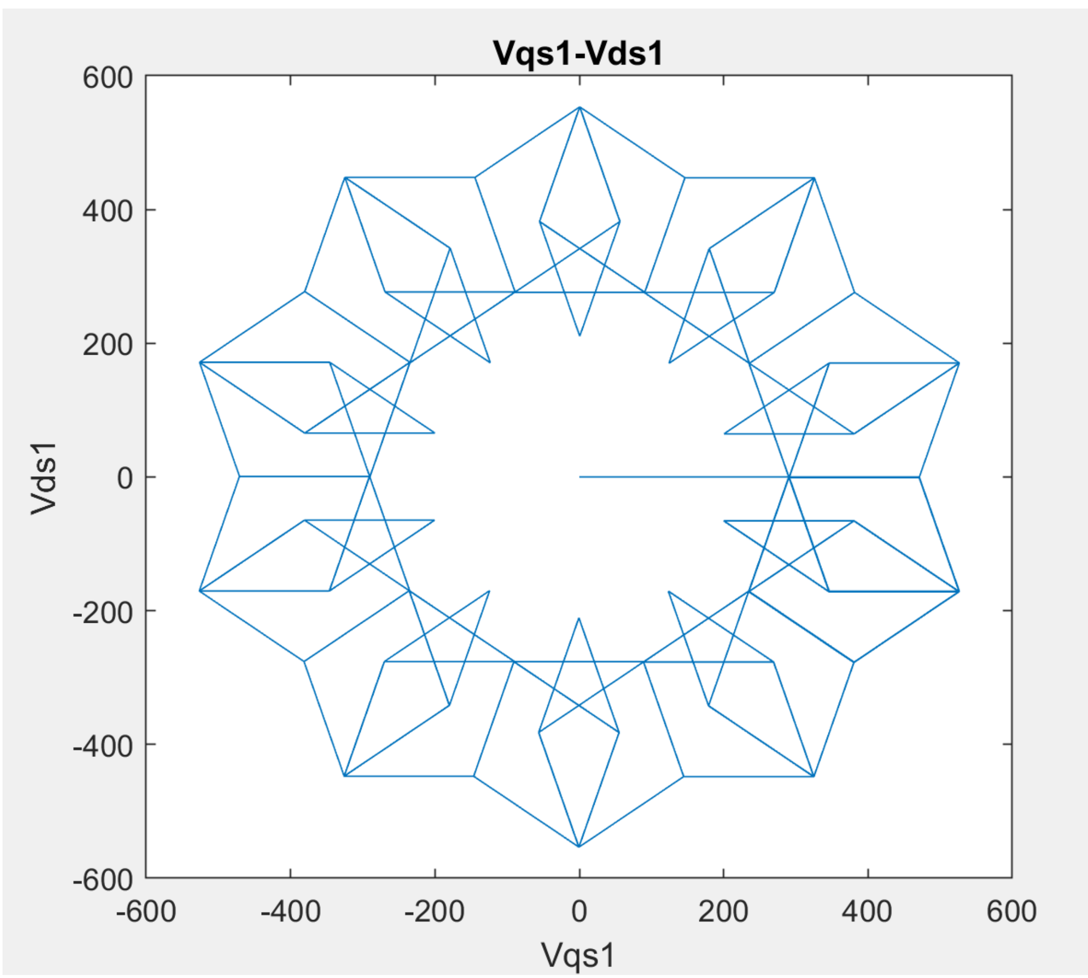

Figure 29 Vds1-Vqs1 plot of harmonics injection (m=0.36)

5 Conclusion

Multi-level multi-phase motor drives have received much attention in recent years. The implementation of multi-phase space vector pulse-width modulation (SVPWM) using MATLAB/Simulink has been described in this paper. By using this model, researchers can trigger the switching sequences in an arbitrary way. In this paper, SVPWM and sine-triangle modulation methods were shown as examples. Then, this paper introduces harmonic injection methods by SVPWM. Researchers prefer to compare these two methods by looking at torque ripple towards reducing torque ripple. SVPWM is more complicated than the sine-triangle method, but it can obtain better harmonic performance and allows design of switching pattern arbitrarily. When using harmonic injection in sine-triangle modulation, researchers should take care of the maximum modulation index and the fixed switching path. In the future research, we can focus on the original switching states plot (243 states) to find a novel algorithm which can transfer the same switching pattern into the sine-triangle modulation.

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