MIDDLE EAST TECHNICAL UNIVERSITY
Electrical & Electronics Engineering

Simulation Project

EE 462 – Utilization of Electric Energy

EE-464 – Static Power Conversion II

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INTRODUCTION

We need to make a simulation project for EE462 and EE464 courses. The aim of this project is designing a motor drive by using sinusoidal PWM for surface mount permanent magnet synchronous machine. For controlling motor, we implemented a current and speed controller by using id-iq parameters. We cannot use Simulink blocks. Therefore, we need to create our own blocks. For part B, we should use sinusoidal PWM technique. Also, in part D, we select the ideal component for project.

PART A: PRE-DESIGN STAGE

1-) We know a relation between torque and power. By using that equation, we can find the rated speed.

$$P = w_{mech} * T_{nominal}$$

w_{mech} = 266.67 rad/sec

T_{rated}=300 N.m

The rated torque is given the specification.

2-) Maximum speed is given the specification. By using that, we can find maximum applied frequency.

$$n_s = 120 * \frac{f}{p}$$

fmaximum is 467 Hz. For switching frequency, we should take it at least 21 times of fmaximum. We can choose the switching frequency as 10 kHz.

3-) The ripple value of input voltage is not specified but we want almost DC voltage and we can choose the ripple value as %2. We can use below equation

$$C = \frac{\Delta Q}{\Delta V} = \frac{I}{f * \Delta V}$$

Where I=250A (maximum motor current), f=300 Hz (since three phase rectifier output)

When we calculate by using that equation, we find DC link capacitor value as 83 mF.

In order to test DC capacitor, we need to calculate resistance value. We know voltage value (565 V) and rated current (120A). Then, we calculate resistance as 2.16 ohm.

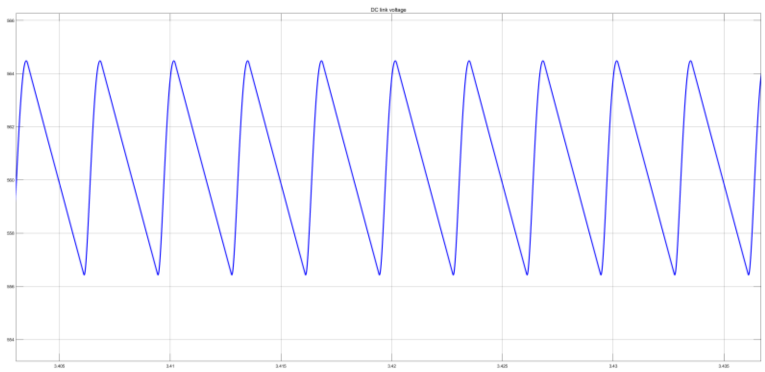

Figure 1: Output waveform of DC link voltage

Therefore, we established the circuit and tested it. We can see the voltage waveform in the figure 1. And, ripple value is %1.5.

PART B: SINUSOIDAL PWM

We can see the whole block diagram of our system in the figure 2.

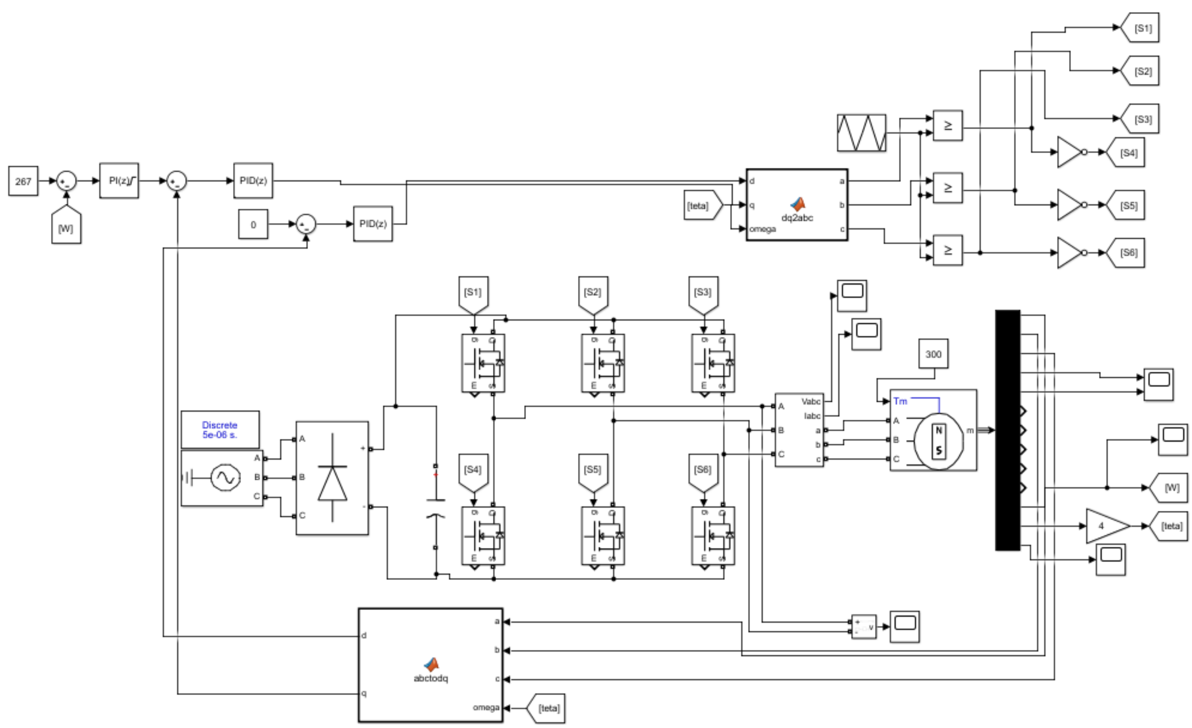

Figure 2: Whole block diagram of motor drive

1- In this part, we should 60 Nm constant torque load to motor input torque parameter. However, firstly, we need to give %90 of rated speed. Then, after reaching steady state, we need to give rated speed as speed reference.

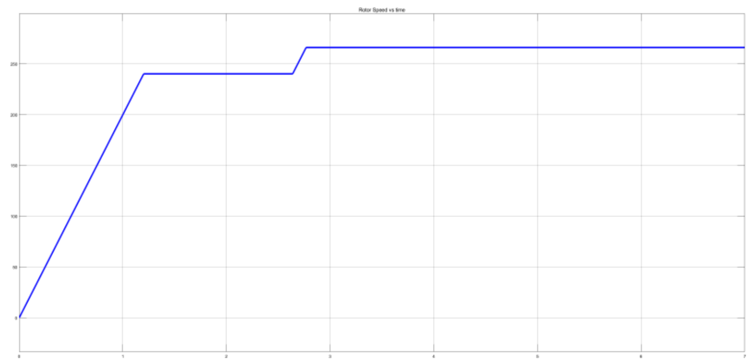

Figure 3: Rotor Speed(rad/sec) vs time(sec) characteristic

When we change the speed reference, as seen in the figure 3, motor reaches the steady state in short amount of time.

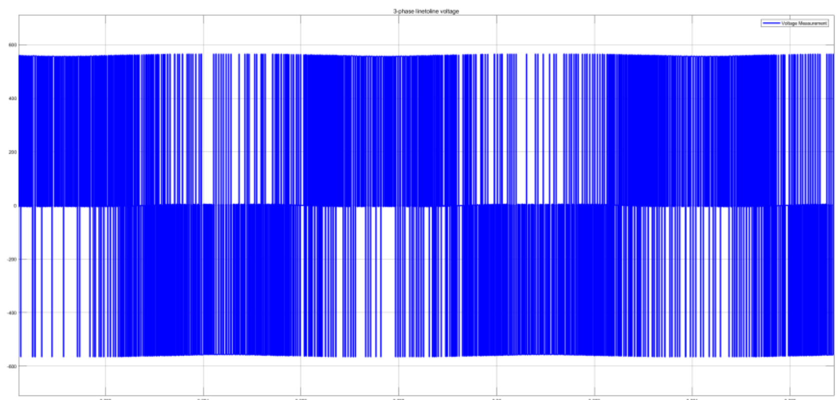

Figure 4: VAB linetoline voltage from a distance

In the figure 4, we see the V_{AB} line-to-line voltage. However, in the real sinusoidal pwm technique, we should not see like this waveform. We should see like in the figure 5. The reason is that frequency and magnitude of references are changing continuously. Due to that, we do not see proper waveforms.

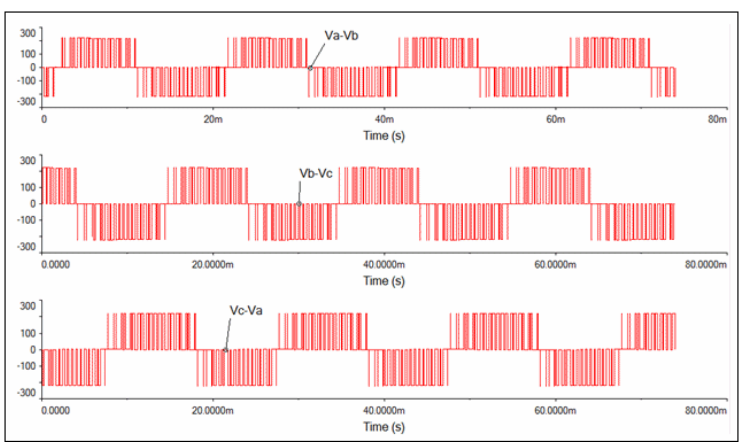

Figure 5: Sinusoidal pwm output waveforms

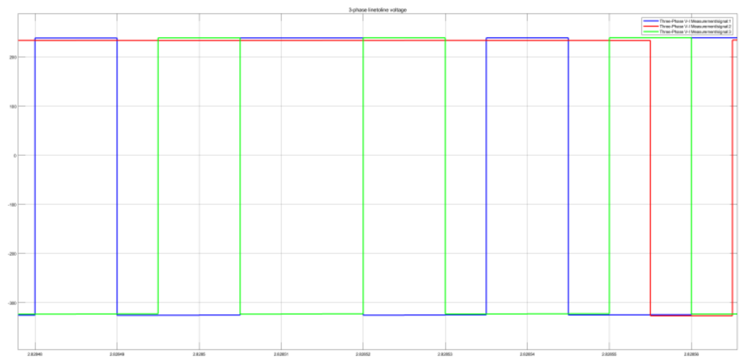

Figure 6: Three phase line voltages upon close look

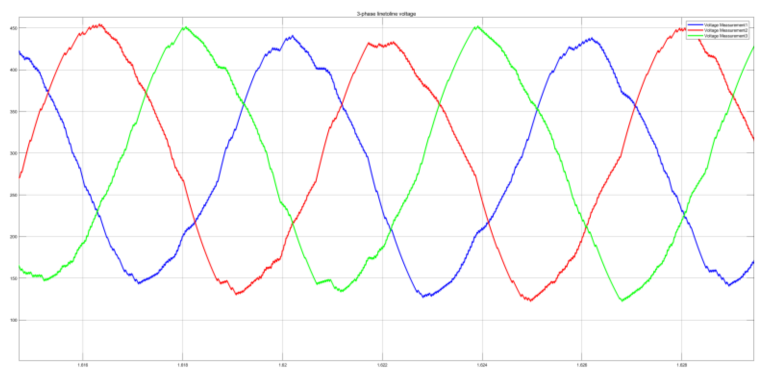

Figure 7: Three phase line voltages upon close look with low pass filter

The motor 3 phase voltages are not obvious since they occur from square wave like in the figure 6. However, when we added low pass filter to output of inverter voltage, we can see clearly the sinusoidal waveforms in the figure 7.

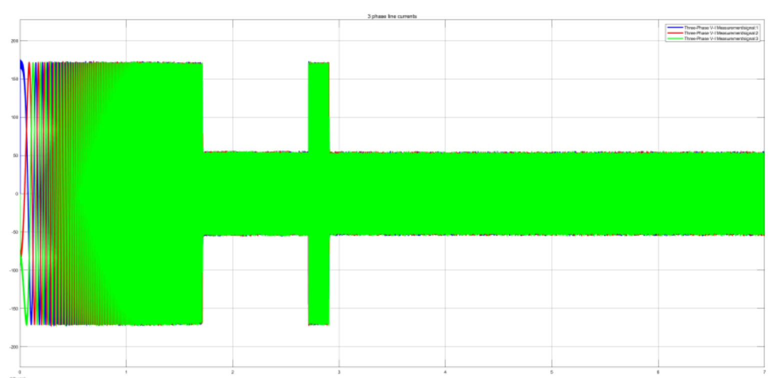

Figure 8: VABC line currents from a distance

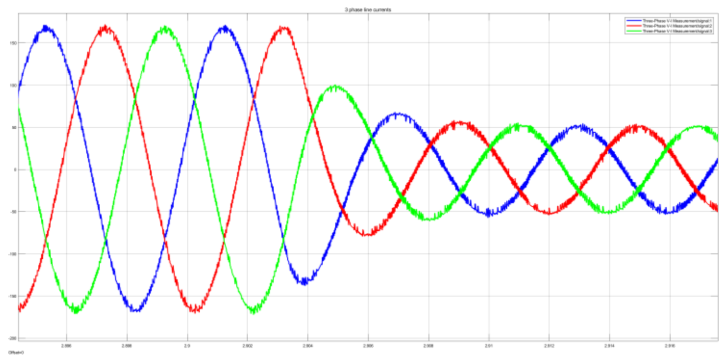

Figure 9: Three phase line currents upon close look

In the figure 8, we see the waveform of line currents from a distance. In the beginning of the simulation, motor draws huge current that is starting current. Then, when it reaches to steady state, current value decreases. In a moment, we change the speed reference, motor draws huge current to speed up. After reaching to the steady state, current decreases. We see this relation in the figures 10 and 11. One of them means torque and the other means d-q currents. We see that q current is responsible from torque since when torque increases, q current increases and vice versa. Moreover, current waveforms are sinusoidal and we expect these results.

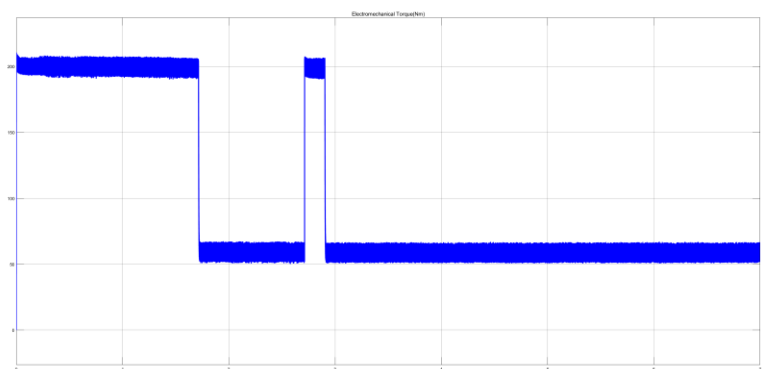

Figure 10: Electromechanical Torque (Nm) vs time characteristic

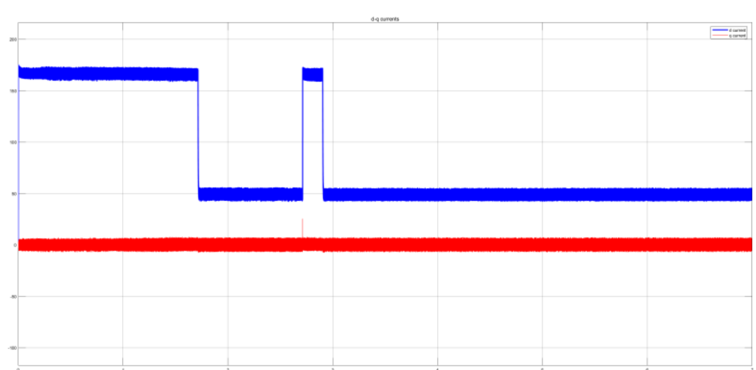

Figure 11: d (blue) and q(red) currents vs time characteristics

2-) In this part, when motor reaches to the steady state, we need to remove load. Then, as seen in the figure 12, rotor speed is changing a little bit, but, after a while, speed becomes reference speed.

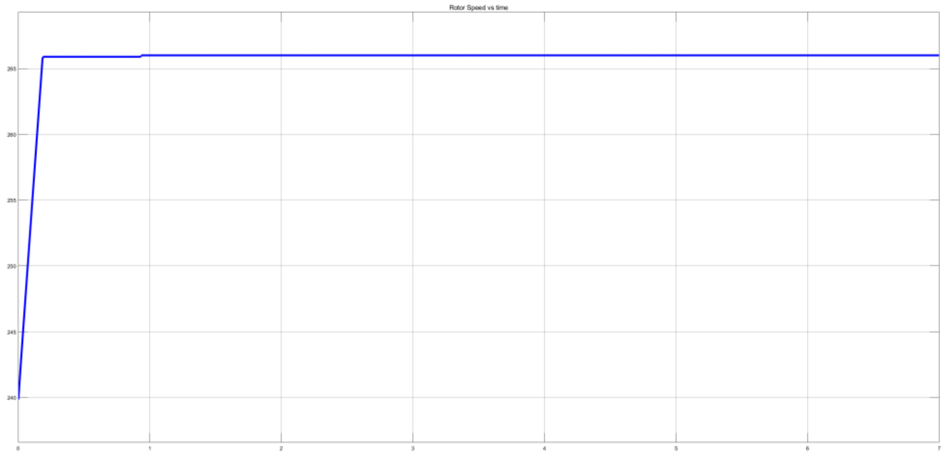

Figure 12: Rotor Speed(rad/sec) vs time(sec) characteristic

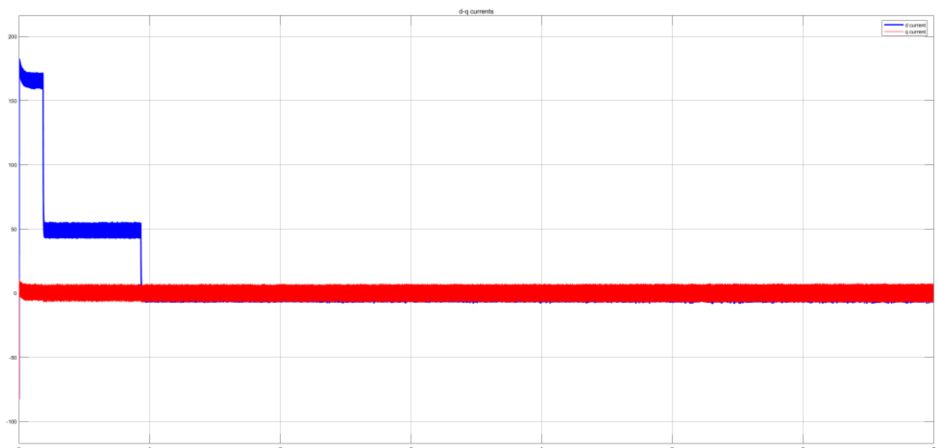

Figure 13: d (blue) and q(red) currents vs time characteristics

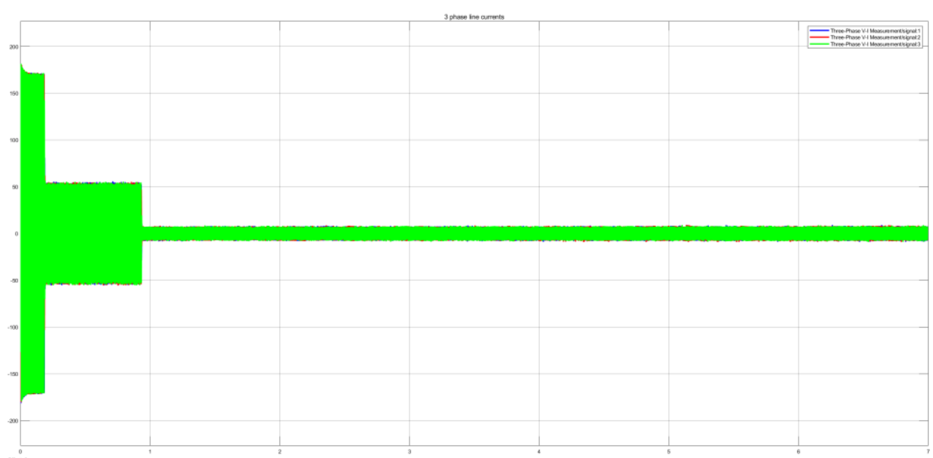

Figure 14: VABC line currents from a distance

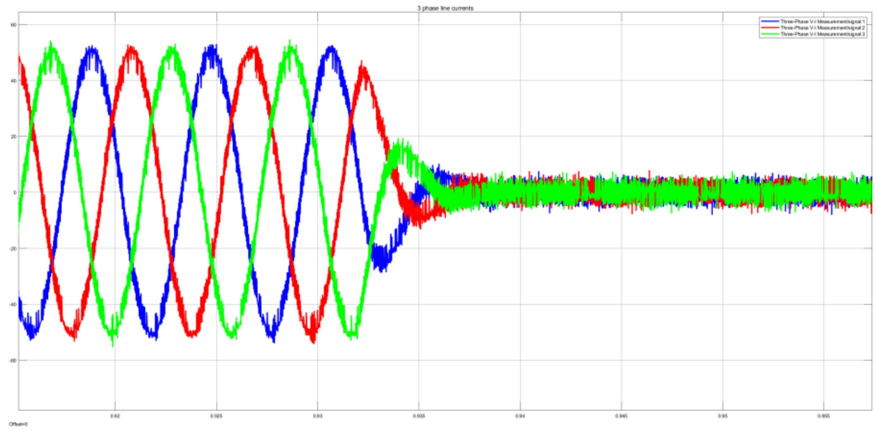

Figure 15: Three phase line currents upon close look

After removing the load, as seen in the figures 13, 14 and 15, all of them decreases. We can mention their relation in the part 1. Again, we that relation.

3-)

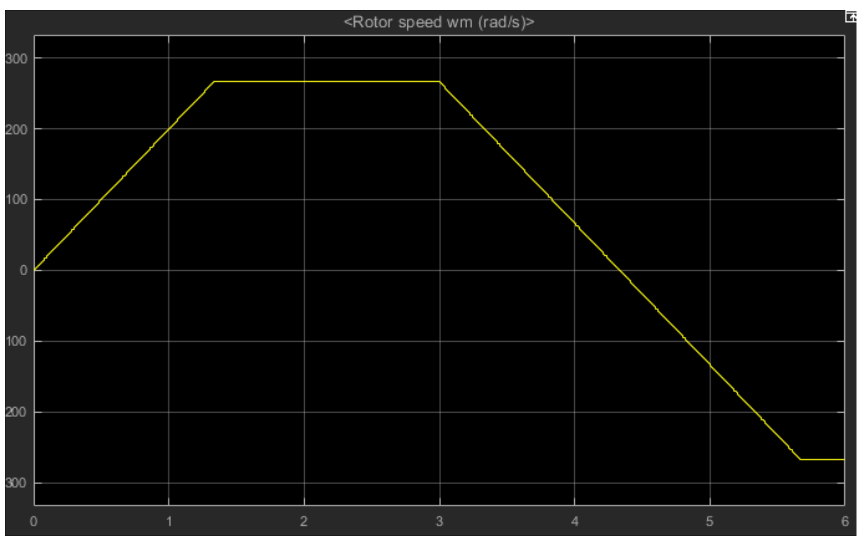

Figure 16: Rotor speed vs time graph

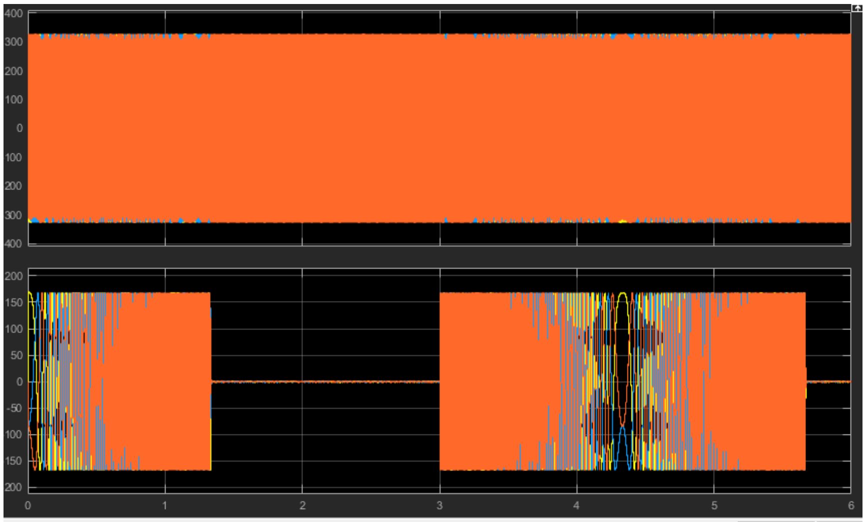

Figure 17: inverter current and voltage output for the 6 second simulation time

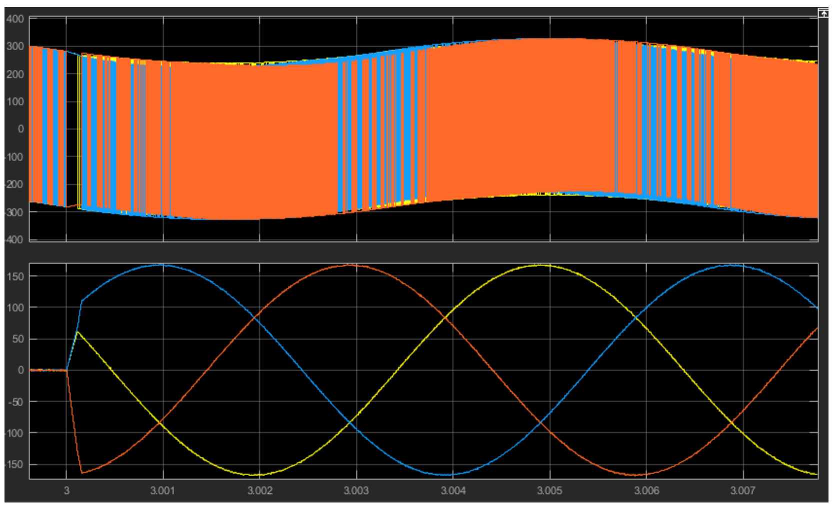

Figure 18: phase currents at the speed reference change

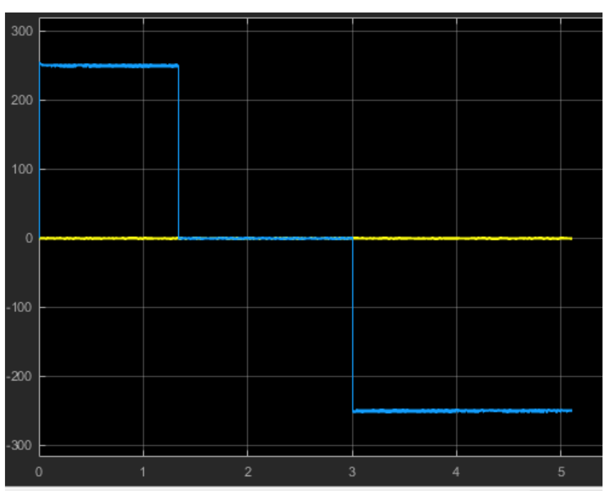

Figure 19:id and iq currents vs time

When the speed reference changes, the motor turns into a generator. Therefore, it starts pumping energy back into the inverter, and through the inverter, to the DC link. Since the diode bridge does not let the excess energy to go back into the grid, the created energy will be stored in the capacitor. However, as the capacitor collects energy, the dc link voltage levels will rise and it could damage the switches, capacitor or the diodes. In order to prevent this, we can add a resistance to dissipate the excess energy. The simulations above are done with the resistance. On figure below, we can see the voltage increase when there is no resistor.

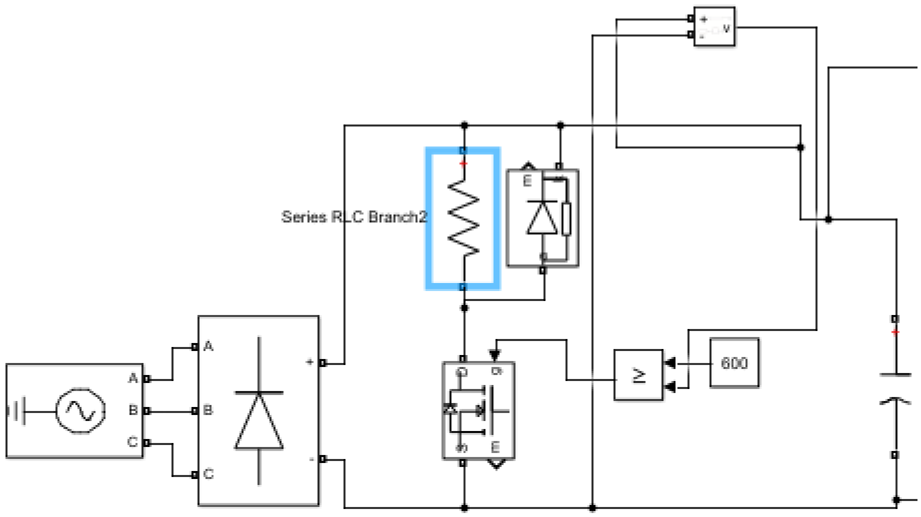

Figure 20: The breaking resistor circuit.

Also, notice that we have lowered the inertia value to 1 in order to have a shorter simulation time.

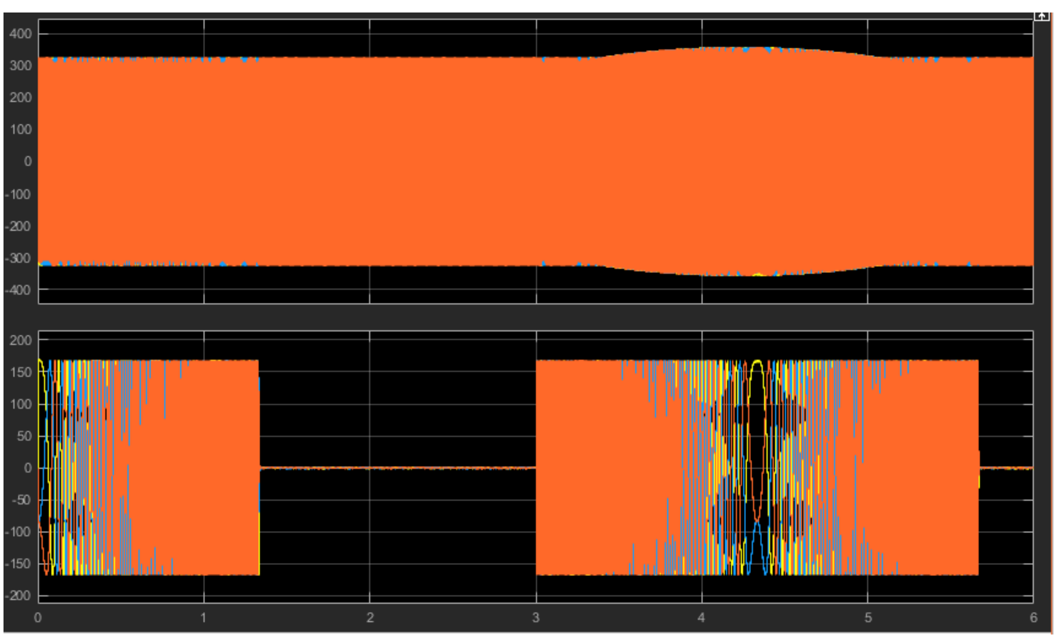

Figure 21: the waveforms when there is no breaking resistor. Notice the CD ling going fat

4-)

We can go into field weakening region to increase the speed.

Firstly, we need to figure out the iq value to provide half the rated torque.

$$T_{mech} = \frac{3}{2} pp \lambda_{mf}^{r} i_q$$

- ⇨ Iq = 125 A

We can use the following formula to figure out the id value.

$$\sqrt{(L_d i_d + \lambda_{mf}^{r})^2 + (-L_q i_q)^2} = L\sqrt{(i_d + \lambda_{mf}^{r}/L)^2 + (-i_q)^2} \le \frac{V_{dc}}{\omega\sqrt{3}}$$

- ⇨ Id = -45.45 A

In order to achieve this, we simply set the reference value of the id current o -45.45 A. After running the simulation, the speed characteristics are as follows.

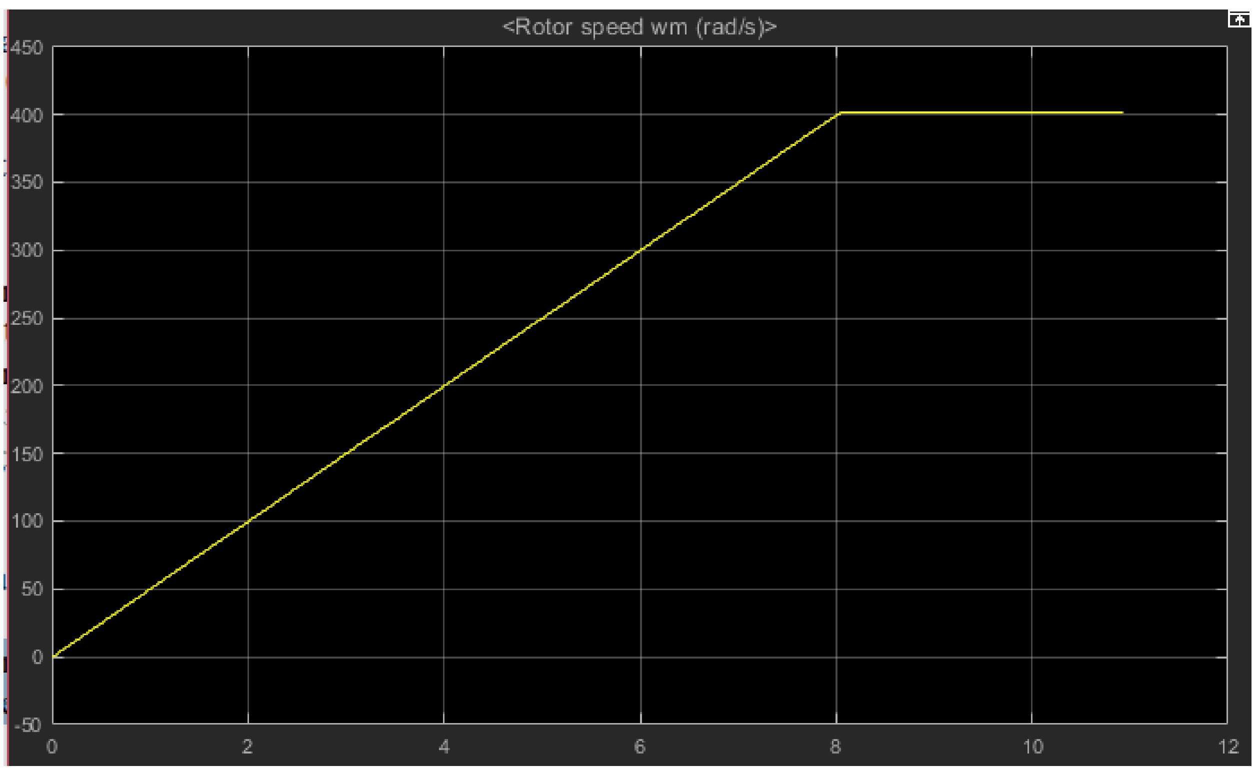

Figure 22: speed vs time graph of the rotor

PART C: SPACE VECTOR PWM (SVPWM)

1-) For this part, we need to use space vector pwm technique. For generating space vector, we use Simulink block. That block takes alfa-beta transformation result as input and generates gate signal with respect to space vector modulation.

We need to arrange the reference speed as %90 of rated speed. After reaching the steady state, we need to change the reference speed as rated speed. We took the same result with part B for speed as seen in the figure 23.

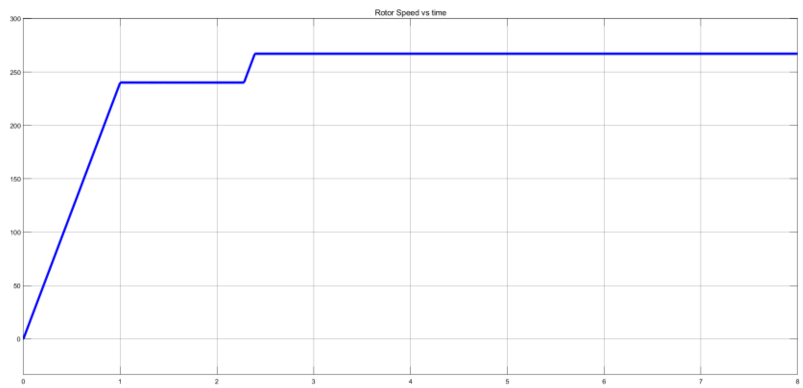

Figure 23: Rotor Speed(rad/sec) vs time(sec) characteristic

The shape of current and torque waveforms looks like the same, but the magnitudes are not the same since in the space vector modulation technique, effective phase voltage and current increase. Therefore, we see that changes in the figure 24, 25 and 26.

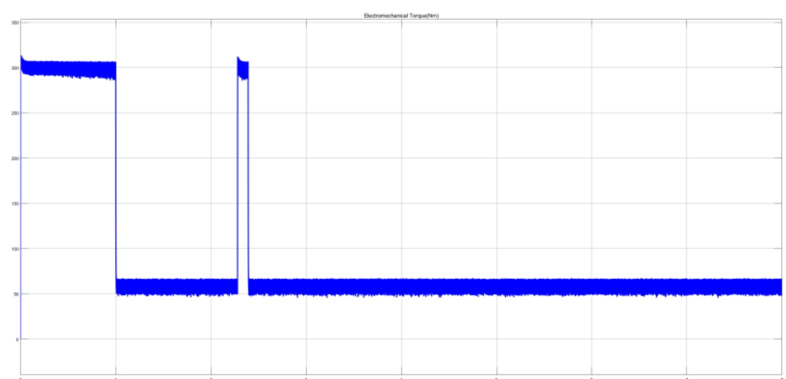

Figure 24: Electromechanical Torque (Nm) vs time characteristic

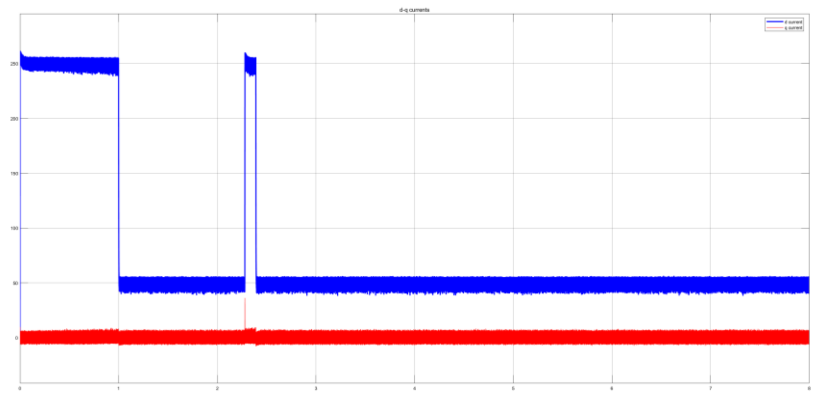

Figure 25:d (blue) and q(red) currents vs time characteristics

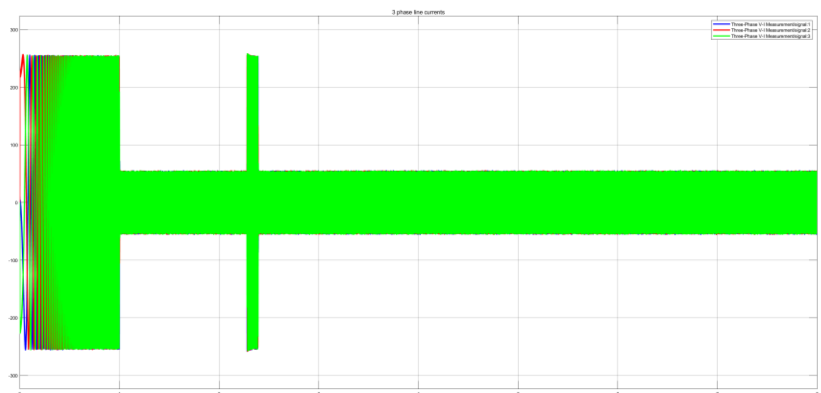

Figure 26: VABC line currents from a distance

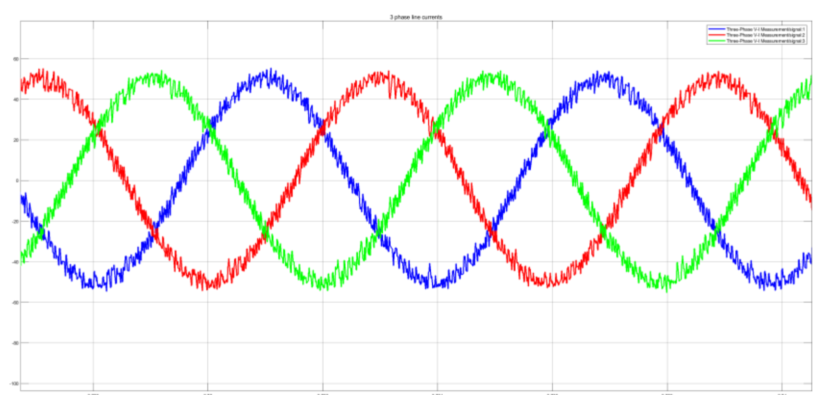

Figure 27: Three phase line currents upon close look

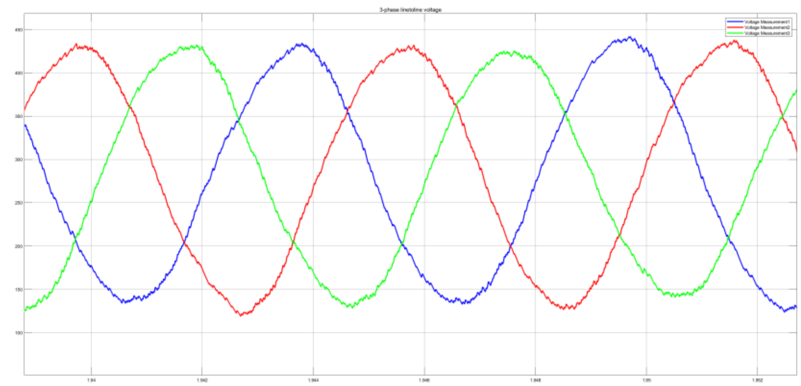

Figure 28: Three phase line voltages upon close look with low pass filter

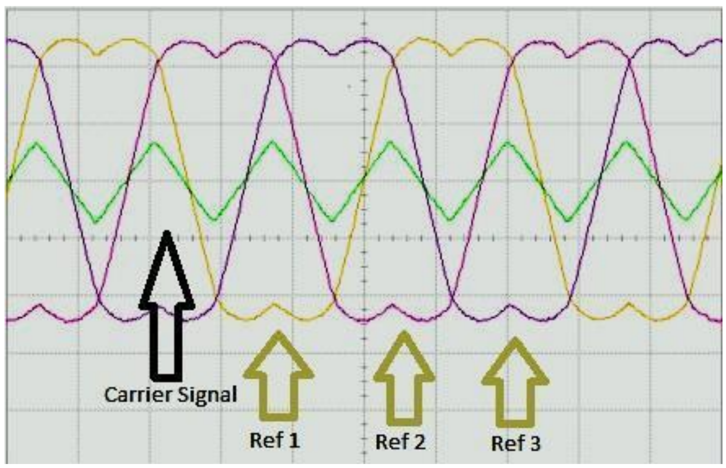

Figure 29: Three phase reference voltage of SVPWM

In the figure 28, we see the reference switching voltage of SVPWM output. However, we did not expect this result. The waveforms should be seen like in the figure 29. The problem can be that we could not use the Simulink block proper or reference voltages is changing continuously.

In the second part, when motor reaches to the steady state value, we need to remove the load. We simulate this test condition. In the figure 30, we can see the speed changing and it is changing a little bit.

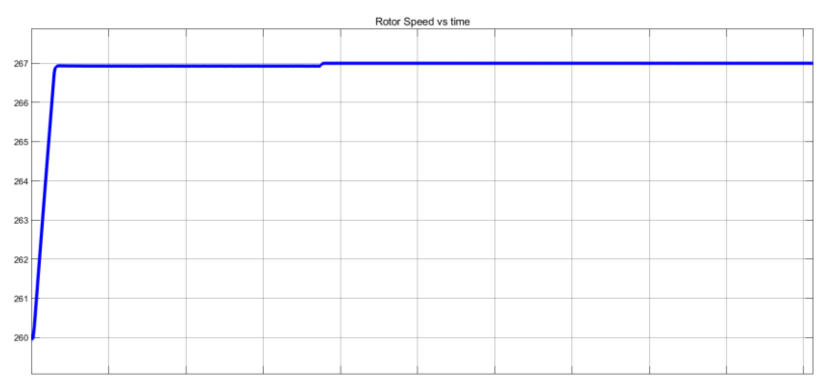

Figure 30: Rotor Speed(rad/sec) vs time(sec) characteristic

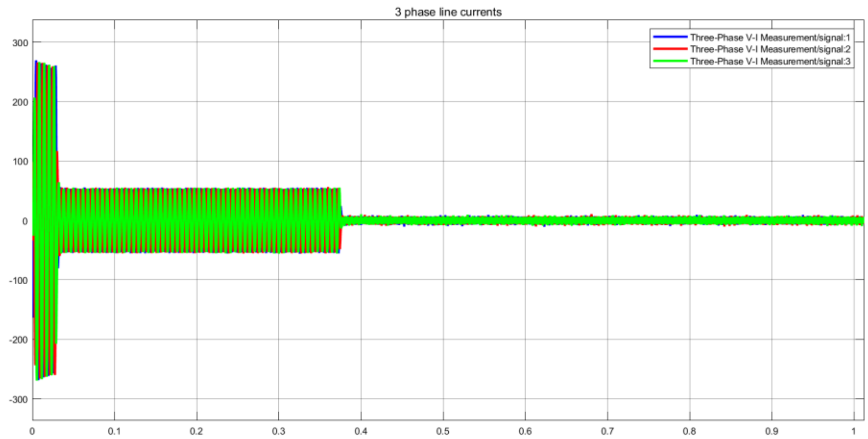

Figure 31: VABC line currents from a distance

In the figure 31, we can see current changing. It is the same with SPWM technique, but current magnitudes are not the same. In the figure 32, output is, also, zero.

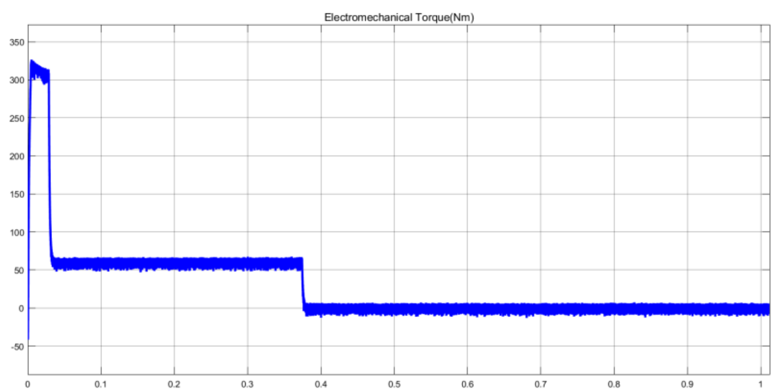

Figure 32: Electromechanical Torque (Nm) vs time characteristic

2-) The SVPWM technique gives higher level of fundamental voltage as compared to SPWM. The comparison of these two modulations gives the results that SVPWM is the best and most reliable modulation because it enables efficient use of DC voltages and smartly works with vector control thus, gives less Total Harmonic Distortion (THD), better PF, and less switching losses at high frequencies.

3-) In this part, we need to observe 3-phase reference voltages. As these waveforms are square waveform, to observe clearly, we put a low pass filter. As seen in the figure 33, there are huge distortion compared to in the figure 34. Also, Waveforms in the figure 33, looks like triangular. However, waveforms in the figure 34 looks like more sinusoidal. We expected these results since we learned that spwm has huge distortion.

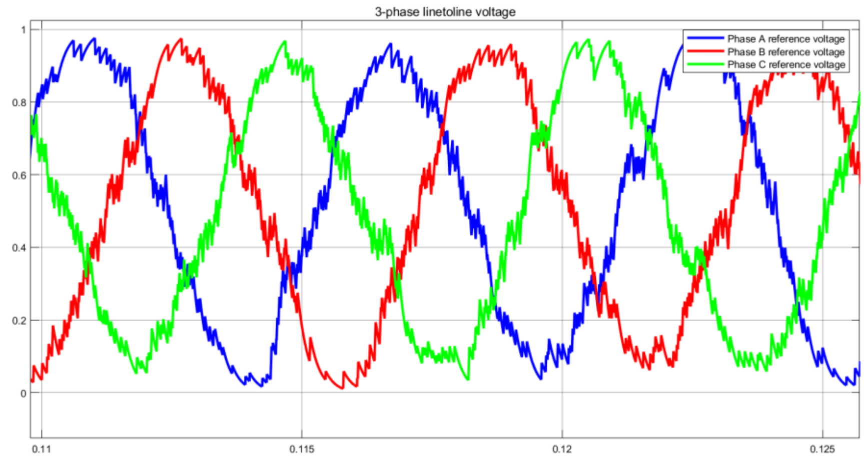

Figure 33: Sinusoidal PWM phase reference voltages

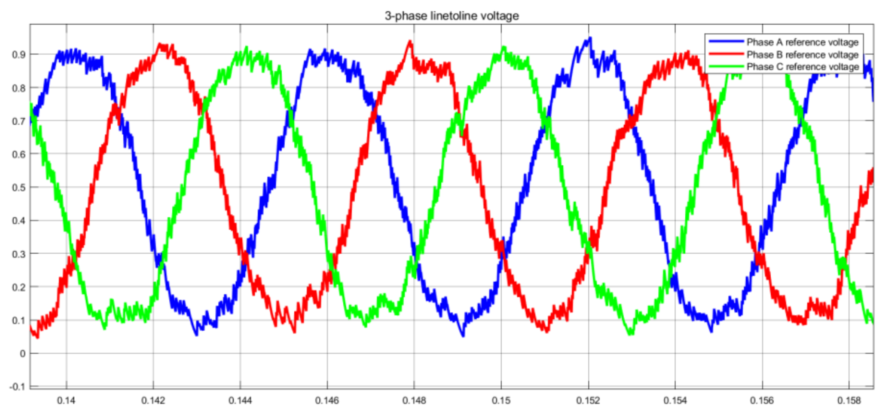

Figure 34: Space Vector PWM phase reference voltages

PART D: COMPONENT SELECTION AND VERIFICATION

For the bridge rectifier:

Since our DC link is maximum at 600 V, and we know the power of the motor (80 kW). Therefore, the dc link current should be around 130 A. so we need diodes that can conduct 130 A and can withstand at least 600 V.

Therefore, we can use this full bridge rectifier:

http://www.vishay.com/docs/94354/vs-130mt80k.pdf

Von is 1.5 V, and there will be two diodes conducting at a time. Therefore,

Ploss = 1.5 *2 *130 = 390 W

For the inverter transistors:

Irms= 175/sqrt(2) = 124 A

When we look at the IGBT's that can handle 200 A and 650 V, we find this bad boy:

With the datasheet:
https://www.littelfuse.com/~/media/electronics/datasheets/discrete_mosfets/littelfuse_discrete_mosfets_n-channel_ultra_junction_ixfn170n65x2_datasheet.pdf.pdf

Let's find the conduction losses:

Rds = 13 mohm => Irms^2 *Rds = 200 W per MOSFET.

Since we have 6 of them: 1200 W for MOSFET conduction losses

From the application note http://www.ti.com/lit/an/slyt664/slyt664.pdf:

Switching loss is:

$$P_{SW} = V_{IN} \times I_{OUT} \times f_{SW} \times \frac{(Q_{GS2} + Q_{GD})}{I_G}$$

Vin = 600 V

Iout= 124 A

Fsv = 10 kHz

Qgs2 = 166 nC

Qgd = 137 nC

Ig = 1 A

- ⇨ Psw = 112.5 W

  For 6 switches:

  Psw = 6* 112.5 = 1300 W

As the current passes from the motor, Rs will also dissipate energy.

Depending on torque this loss will change. At max torque, iq will be 250 and therefore:

Pmotor = 250^2 * 0.05 = 3125 W

Total loss:

Pmosfet = 1300 + 1200 = 2500 W

Pdiode = 390 W

Psemiconductor = 2890 W

Pmotor = 3125 W

Ptotal = 6 kW

- ⇨ Eff = 80000/86000 = %93

CONCLUSİON

The aim of this simulation project is designing a motor drive with respect to id-iq current parameters. We made this control by using sinusoidal and space vector PWM techniques. By changing speed or torque references, we observed the change of waveforms. The last part, to implement this controller in the real life, we choose proper components. Then, we calculated the power losses and efficiency.