MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICS ENGINEERING

EE462 - UTILIZATION OF ELECTRICAL ENERGY

TERM PROJECT

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Contents

1 Part A - Pre Design Stage

1.1 Q1

In this part, we are asked to calculate the rated torque of the motor.

$$T_{rated} = \frac{P_{nominal}}{\omega_{nominal}} = \frac{400kW}{50\pi} = 2546\ Nm \tag{1}$$

1.2 Q2

In this part, we are going to calculate the rated frequency of the machine, and depending on the maximum frequency, we will choose a switching frequency.

$$f_{m,max} = \frac{2250}{60} = 37.5Hz, \tag{2}$$

$$f_{max} = f_{m,max}pp = 75Hz \tag{3}$$

As we increase the switching frequency, the losses will increase. So, we need to choose an adequate switching frequency. Also, to eliminate the lower harmonics we are going to choose a large switching frequency.

We choose the switching frequency as

$$f_s = 3000 \tag{4}$$

1.3 Q3

We know that DC voltage of a three phase full wave rectifier is:

$$V_{DC} = 1.35V_{L-L} \tag{5}$$

Therefore, 540V is obtained with the three phase full wave diode rectifier. In order to design a reasonable DC link capacitor, the peak current which is 1700A is considered, and machine is represented with a 0.317 ohm resistor. Desired voltage ripple is decided, and required capacitance value is found from the following schematic.

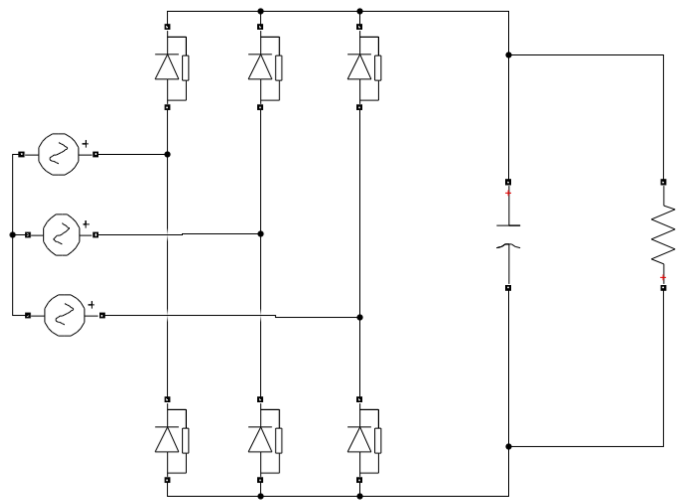
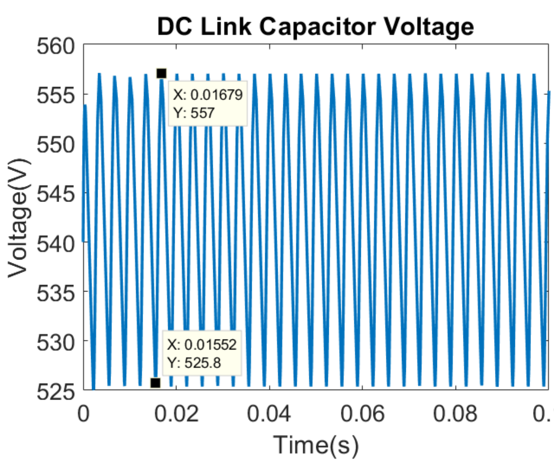
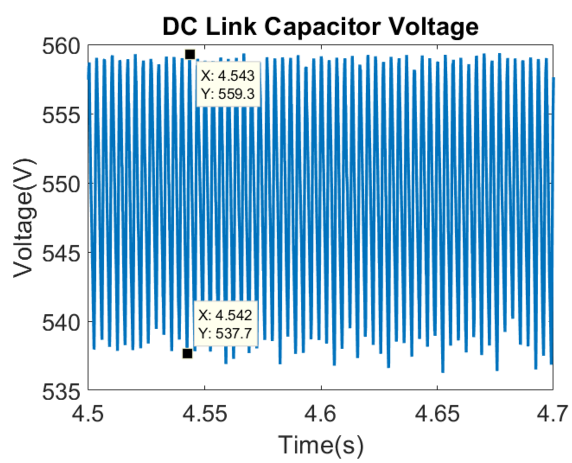


Figure 1: Circuit Schematic with Representative Resistor

For such a system, it is appropriate to have nearly 6% voltage ripple. From simulations shown in Fig. 2a, it is obvious that nearly 5.8% voltage ripple is obtained with 100 mF capacitor.



(a) DC Link Capacitor Voltage with Resistive Load



(b) DC Link Capacitor Voltage $f_s = 3kHz$

Figure 2: DC Link voltage for Resistive Load (a) and SPWM (b)

With an inverter, it is known that voltage ripple decreases due to switching frequency. In other words, obtained 5.8% ripple decreases more with the inverters. When the 100 mF capacitor is used in SPWM, voltage ripple is decreased to nearly 4% which is shown in 2b.

2 Part B: Sinusoidal PWM

2.1 Q1

In the Fig 3 below, we can observe the speed vs time graph of the pmsm motor. Here, we can see that the motor is speeding up from its 90% rated speed to its rated speed.

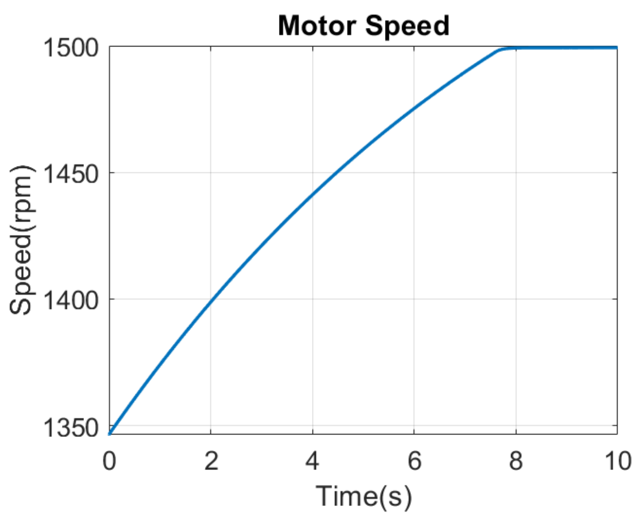
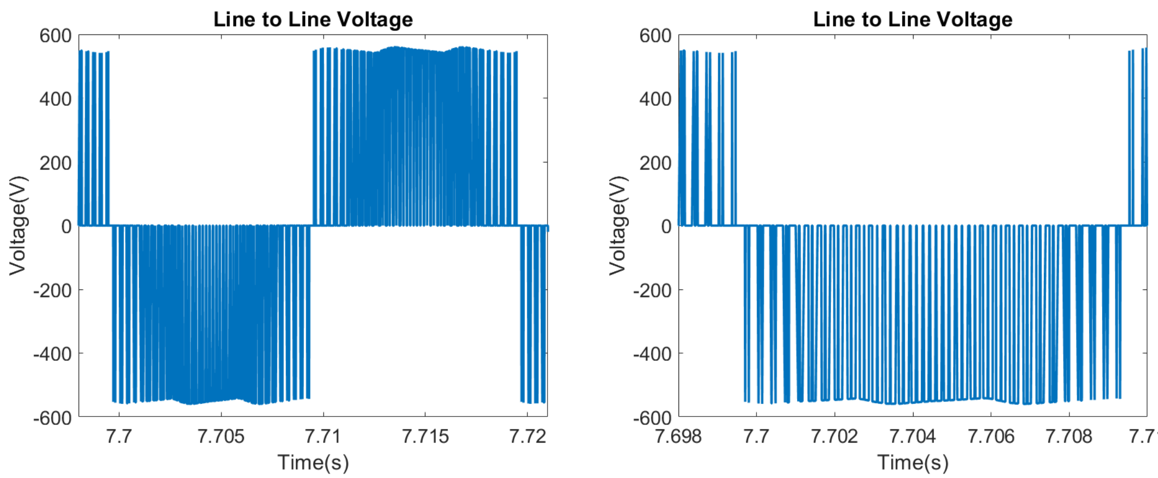


Figure 3: Speed vs time graph of the motor

In the Fig. 4a and Fig. 4b below, we can observe the line to line voltage vs time. System does not reach the voltage limit since it is not on the maximum torque line. Nevertheless, it is very close to voltage limit.

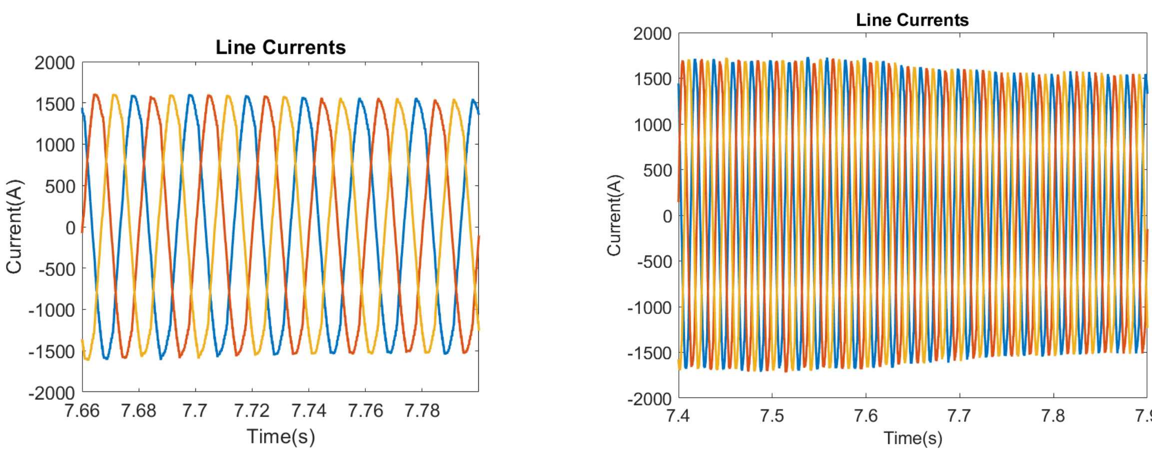


(a) Line to line voltage

(b) Line to line voltage, one cycle

Figure 4: Line to line voltage general (a) and one cycle (b)

In the Fig. 5 below, we can observe the phase currents vs time. At transient the currents decrease to their steady state value.

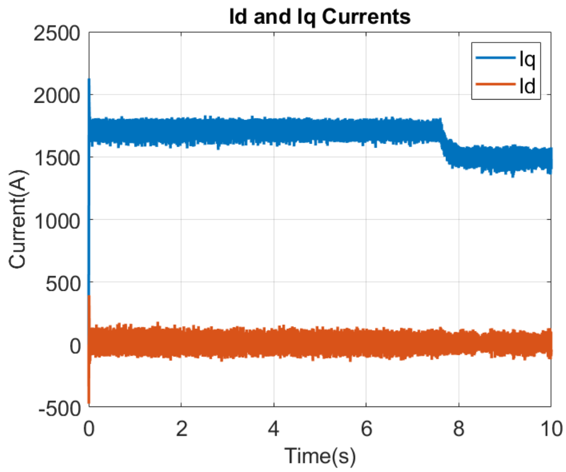


(a) Line current, focused

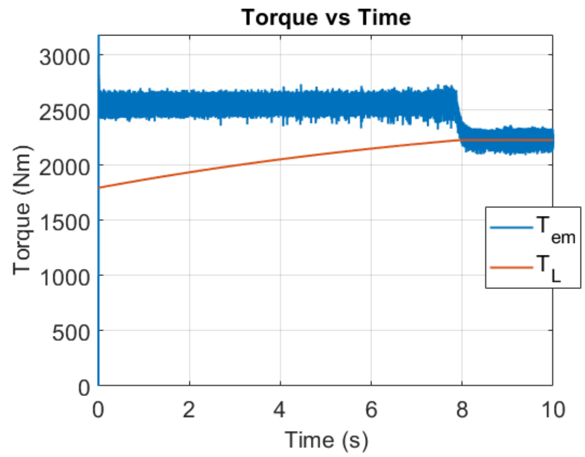
(b) Line currents

Figure 5: Line current focused (a) and general (b)

In the Fig. 6b below, we can observe the machine torque vs time graph. It shows that the torque is increasing due to the load characteristic. In the Fig. 6a below, we can observe the I_q and I_d currents of the motor.



(a) Motor currents in the d-q reference frame



(b) Torque vs time graph of the motor

Figure 6: d-q currents of the stator (a) and torque vs time (b)

We can see from the Fig. 6, the motor i_q current and motor torque are directly proportional to each other. When we are in the transient, i.e. we are speeding the motor up, we apply maximum possible current which is $1700A$, when we reach the final speed, the apply steady state current which can supply enough current to operate the motor in constant speed. The noise is due to the controllers.

We can see that the time to go from 90% to its rated speed is 7.5 seconds!

2.2 Q2

In the Fig. 7 below, we can observe the machine torque vs time graph. It shows that the torque is decreasing after time step $t = 2s$ where we decrease the load torque to zero.

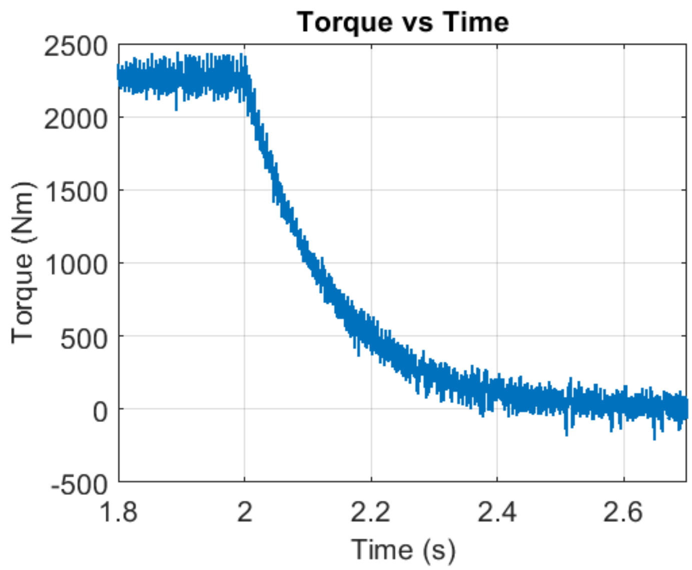
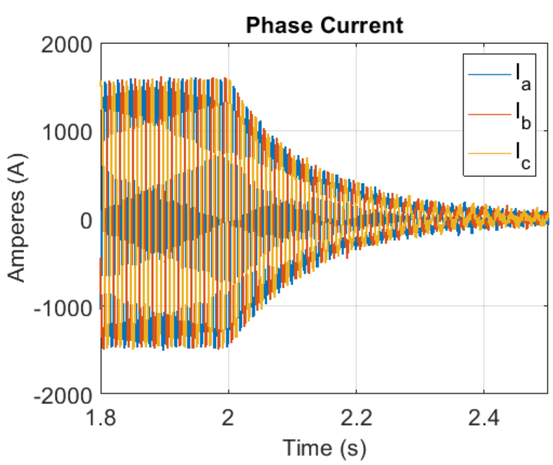


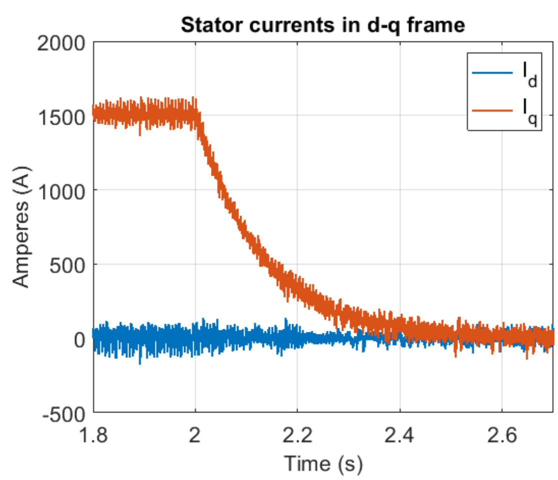
Figure 7: Torque vs time graph of the motor

In this part, we lower the mechanical torque to the zero as we operating in rated conditions. we expect our phase currents to decrease and of course the i_q current which deploys torque to decrease.

In the Fig. 8 below, we can observe the phase currents vs time



(a) Motor line currents during transient



(b) Motor stator d-q currents during transient

Figure 8: Line to line voltage general (a) and one cycle (b)

We can observe that the phase currents are lowering due to decrease in the torque. We know that the torque is directly proportional to the i_q current, and a decrease in the i_q while keeping i_d constant will decrease line currents. After the transient, we have a noise in the line currents due to the inertia of the motor and the noise in the controllers.

As we observe, the I_q current was it in rated value to apply rated torque at rated speed, then suddenly we decrease the load torque. Due to the controller, i_q current decreases to 0 where it provides zero torque, however, there are noise due to the controller circuit and motor itself.

2.3 Q3

We know that during the braking time, the motor supplies current to the utility side, and if we do not have a full quadrant operation or back to back rectifiers, it is not possible to supply energy from load to the grid. In this case of operation as we have in this project, it is not possible to have a current into the grid because of the diode rectifier. So, the solution must be braking resistance. During transient time, the energy stored on the load and the motor can be discharged through this resistor. It prevents the circuit from burn-outs and excessive heating. The braking resistance selection of us is $R = 0.5\Omega$. We can observe the braking resistance schematic below in the Fig. 9. As we follow, we sense the voltage on the capacitor, and when it exceeds 560V, we start to discharge the capacitor over the brake resistance. Here, we simulate the circuit to obtain maximum voltage of 600V during transient time. As we know, the larger resistance mean the greater peak voltage on the capacitor, so we should be careful when selecting the brake. As we mentioned above, the braking resistance is $R_{brake} = 0.5\Omega$

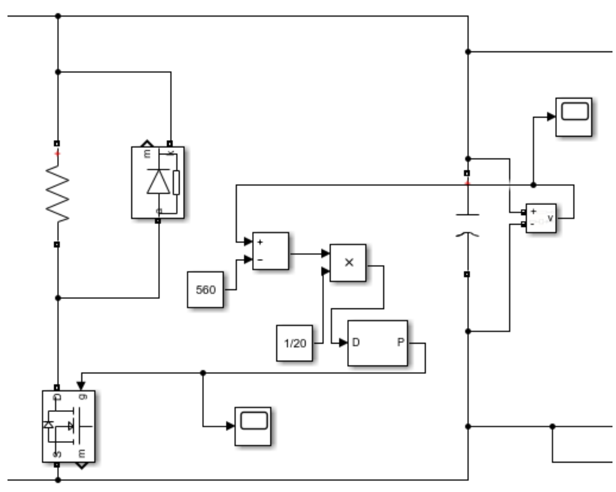
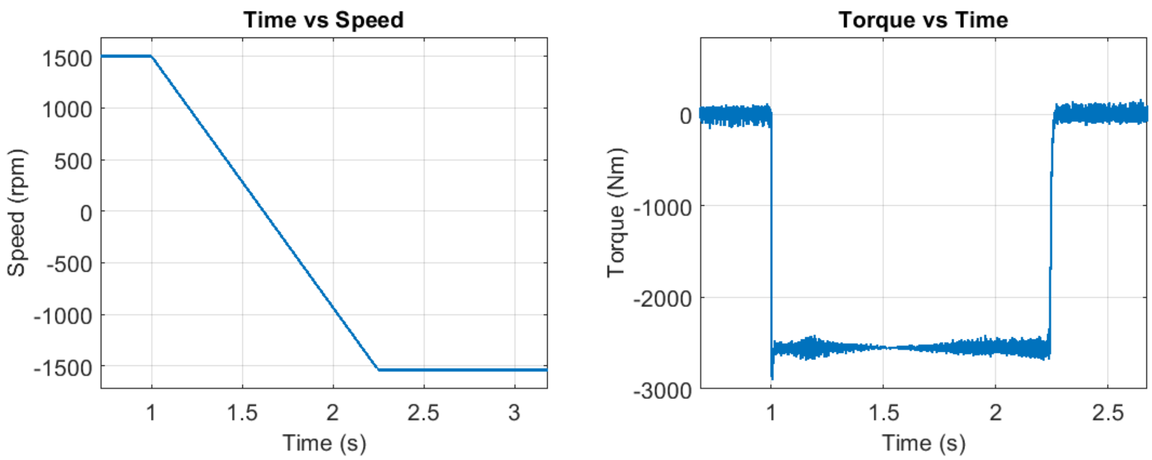


Figure 9: Braking resistance circuitry

In the Fig. 10 we can observe that after we reverse the reference speed at time $t = 1$ the motor speed decreases to 0, and then reversely increases to its final value. Meanwhile, due to the reversal, a negative torque is applied from the motor and it creates a current in the negative direction. This current should be discharged in order to prevent burnouts in the circuitry. Because of this simple phenomenon we introduce a braking resistance to the circuit.

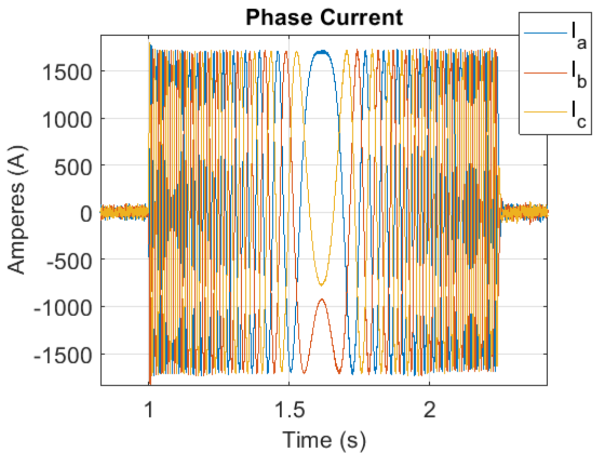


(a) Speed

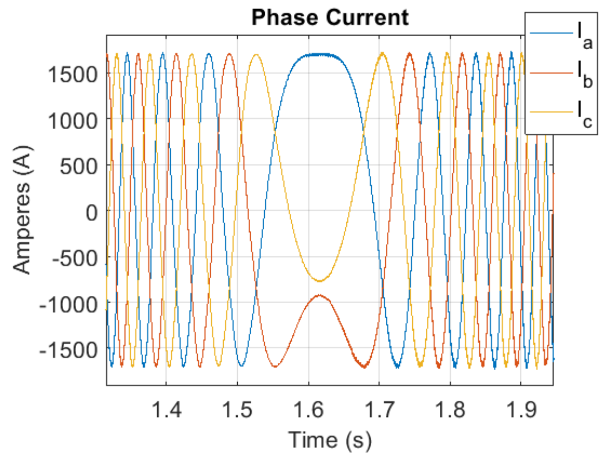
(b) EM Torque

Figure 10: Reversal, speed vs time (a), electromechanical torque vs time (b)

In the Fig. 11 below, we can easily observe that at the steady state we have only noise in the line currents, then when we reverse the speed reference, current is produced in the motor in order to reverse the motor. It deploys power to the utility side as we discussed before. In the Fig. 11b we can see that the frequency of the current decreases to the zero and then increases again. This is due to the reducing speed of the motor and speeding up again.



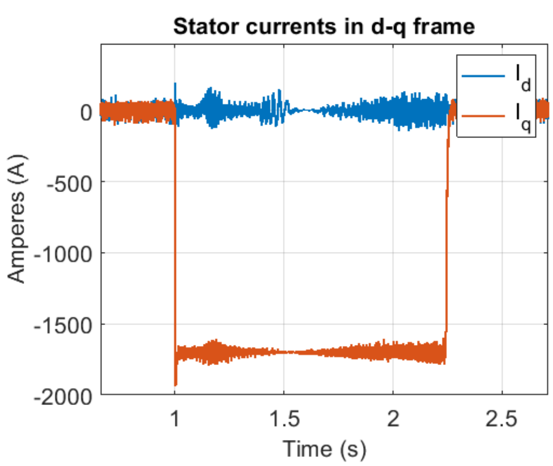
(a) Line currents during reversal



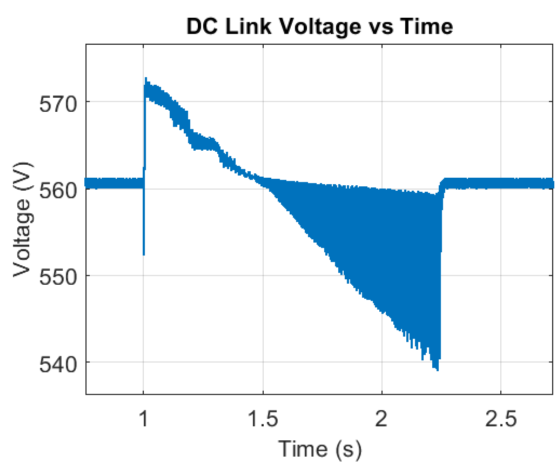
(b) Line currents during rotation direction change

Figure 11: Reversal, line currents

In the Fig. 12 below, we can see that our brake resistor starts operating voltage above 560, that is why in steady state we are constrained by 560V. Then, during the reversal due to the current supplied from the motor side, the voltage increases up to 580V, however, braking resistor allows us to discharge this energy. Then, the voltage is decreased to its final value after a transient period. When we have a look at Fig. 12a we can observe that in steady state both currents are zero with noise, however in the transient time, we have a negative i_q resulted from the motor's reversal. This current discharges over the braking resistance.



(a) Stator currents



(b) DC link voltage

Figure 12: Reversal, d-q currents (a) and DC Link voltage (b)

2.4 Q4

In this part, we need to operate the motor in the field weakening region. For this calculations, i will apply rated current conditions. In the first state, we are in the rated speed with half of the maximum torque. Since i_q and torque is directly proportional, we can find i_q using these relation.

$$i_q = \frac{T_m}{3\lambda} \tag{6}$$

where Torque can be found as:

$$T = 1273Nm$$

When we calculate it:

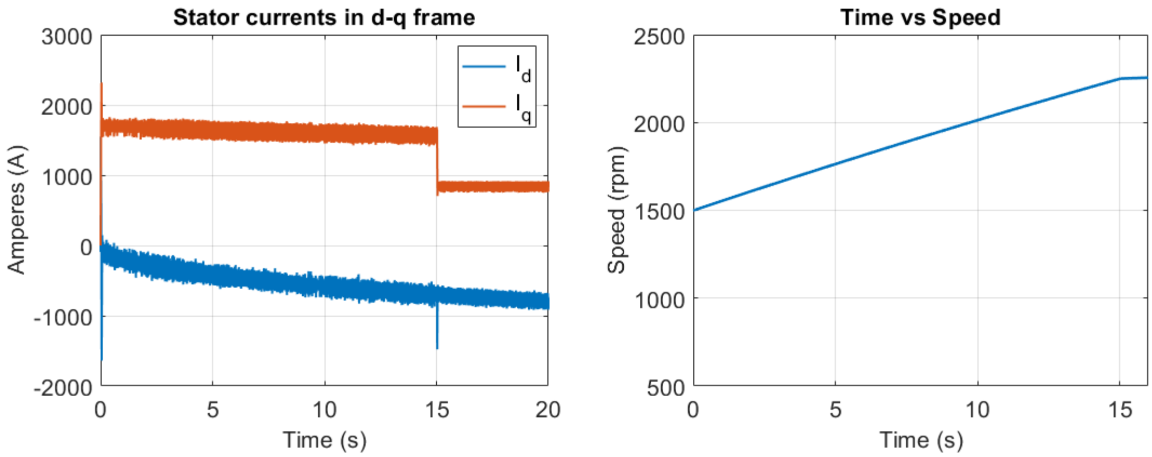
$$i_q = \frac{1273}{1.5} = 848.7A$$

Since we are in the rated speed, we are in the base region which means there is no need of i_d current to speed up the motor. However when we look at the final operation, i am assuming that we are operating in the rated current conditions over the $i_{s,max}$ line. I do not think that this operation makes sense because there is no need to work on the maximum current line. We will suggest another option below!

$$i_q = \frac{1273}{1.5} = 848.7A$$

$$i_d = 1700^2 - i_q^2 = 1472A$$

Now, the point is that these values are steady state values, and to speed up the motor we need to apply additional torque in order to speed up, we need a net torque. For this reason, i apply maximum i_q current available at any time, and i add i_d current when the V exceeds its rated value. The results are shown in the following Fig. 14



(a) Stator currents

(b) Speed vs time

Figure 13: Field weakening, d-q currents (a) and speed vs time

Comments: Normally, in the calculations we made, we found a surprising thing, at the steady state the required i_d current can be calculated in the following limitation:

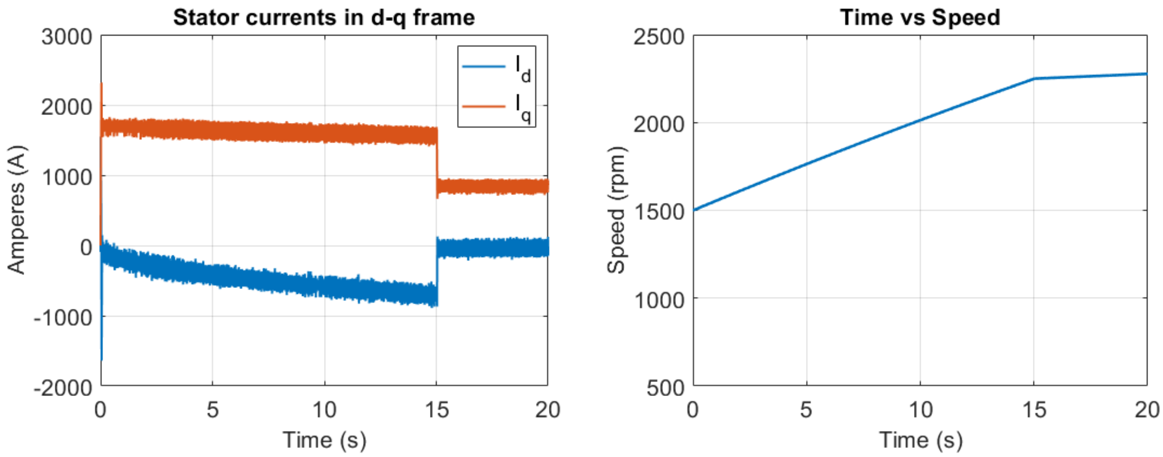
$$V_{max} = \sqrt{(\omega_e \lambda + i_d \omega_e L_d)^2 + (i_q \omega_e L_q)^2)}$$

And when we calculate the required minimum current in the steady state we can find the followings: At the 150% rated speed, the $\omega_e = 471rad$,

$$270 = \sqrt{235.5 - 0.165 i_d)^2 + (140)^2)}$$

So, at this condition we only need $i_d = -28.08A$ if we operate at the rated voltage conditions. However, in the simulations I cannot make it work and I am sharing the numerical results to show that the most logical operation is not the rated current operation, but any other operation with balanced current and voltage. Furthermore, at the transient, we always should supply an i_d current to guarantee that we do not exceed the voltage maximum. It is **NOT** possible to speed up something applying the amount of torque needed to supply to hold a constant operation. In the simulations, we applied maximum i_q current possible to speed up, and then we hold a constant operation with i_q and i_d at this point.

Below, in the Fig. 14 we can observe it. As you can see it is possible to apply just $30A$ of i_d current, and hold a steady state operation at 150% rated speed.



(a) Stator currents

(b) Speed vs time

Figure 14: Field weakening, d-q currents (a) and speed vs time

This operation is much logical because we do not work in the rated current conditions, it decreases losses and decreases the stress on the equipments. Also, it is not necessary to work on the maximum current line because we are not supplying maximum torque at that speed!

3 Part C - Space Vector PWM

3.1 Q1

3.1.1 Q1-1

In the Fig 15 below, we can observe the speed vs time graph of the pmsm motor. Here, we can see that the motor is speeding up from its 90% rated speed to its rated speed.

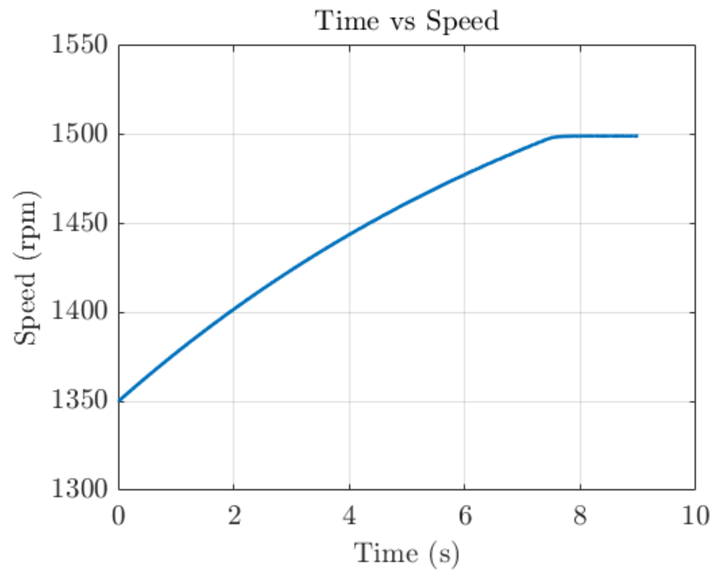
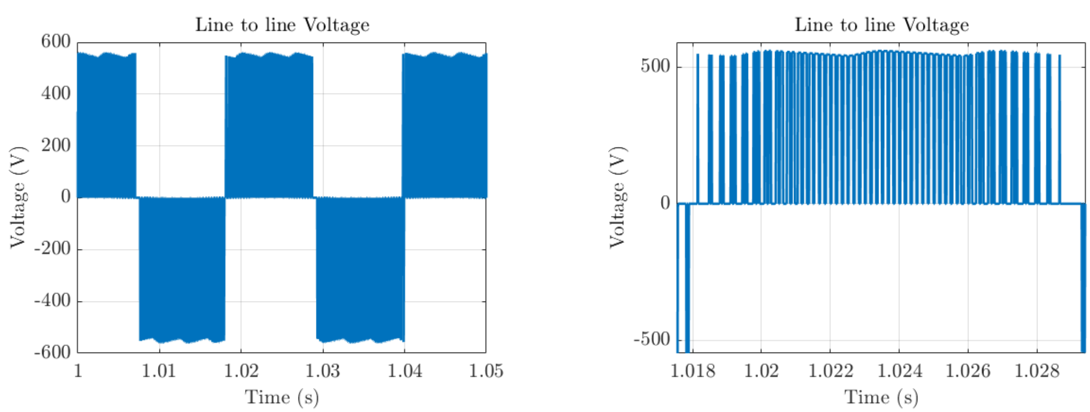


Figure 15: Speed vs time graph of the motor

In the Fig. 16a and Fig. 16b below, we can observe the line to line voltage vs time

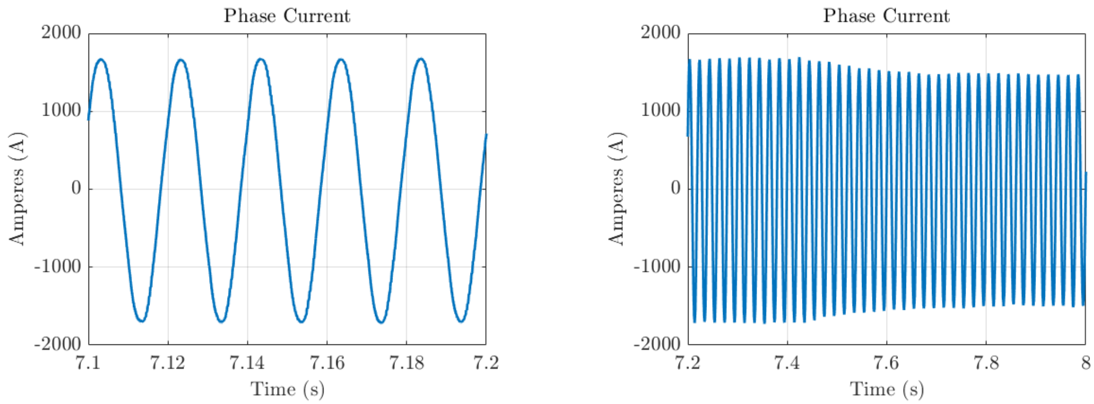


(a) Line to line voltage

(b) Line to line voltage, one cycle

Figure 16: Line to line voltage general (a) and one cycle (b)

In the Fig. 17a and Fig. 17b below, we can observe the phase current, Fig. 17a is the current while the motor is speeding up, and Fig. 17b shows the current when motor reaches its steady state speed.

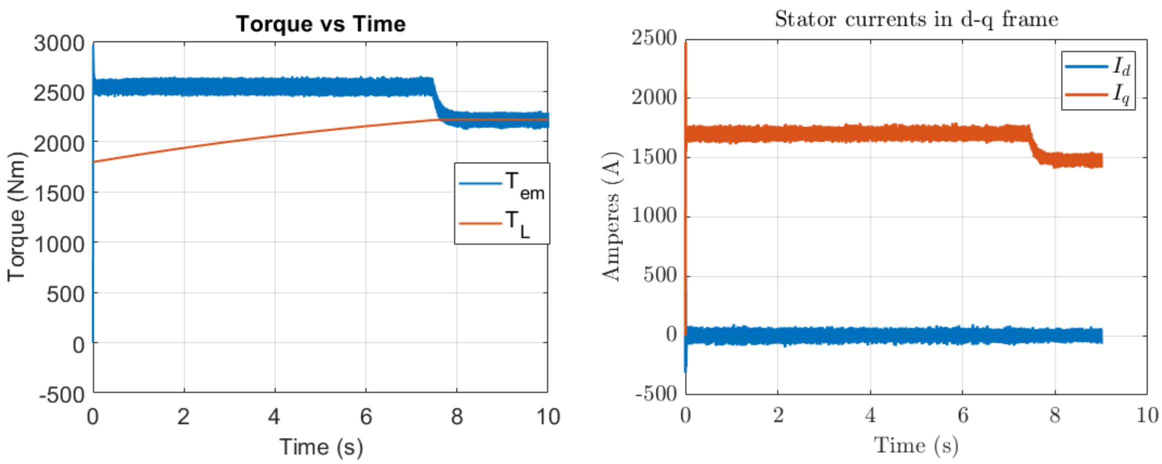


(a) Line to line voltage

(b) Line to line voltage, one cycle

Figure 17: Phase current speeding up (a) and transient to the steady state (b)

In the Fig. 18a below, we can observe the machine torque vs time graph. It shows that the torque is increasing due to the load characteristic. Also, d-q currents in the stator shows a similar transient. Since torque and i_q currents are directly proportional to each other, it is easy to see relation between them.



(a) Torque vs time graph of the motor

(b) Torque vs time graph of the motor

Figure 18: Phase current speeding up (a) and transient to the steady state (b)

3.1.2 Q1-2

In the Fig. 19 below, we can observe the machine torque vs time graph. It shows that the torque is decreasing after time step $t = 1s$ where we decrease the load torque to zero.

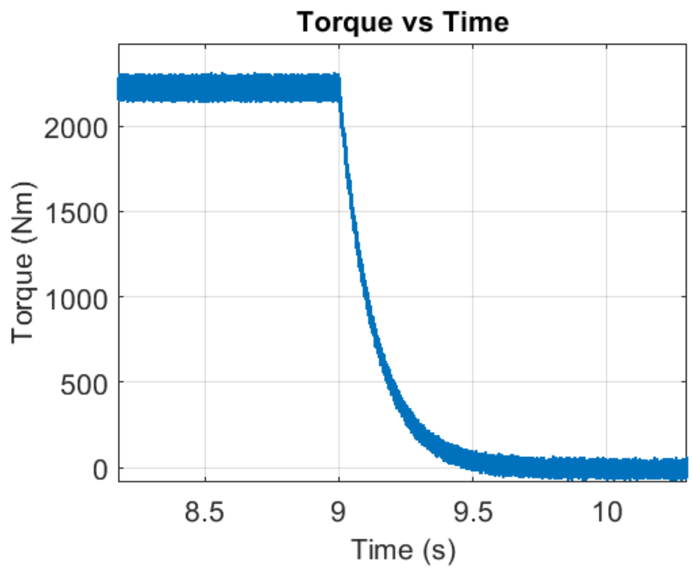
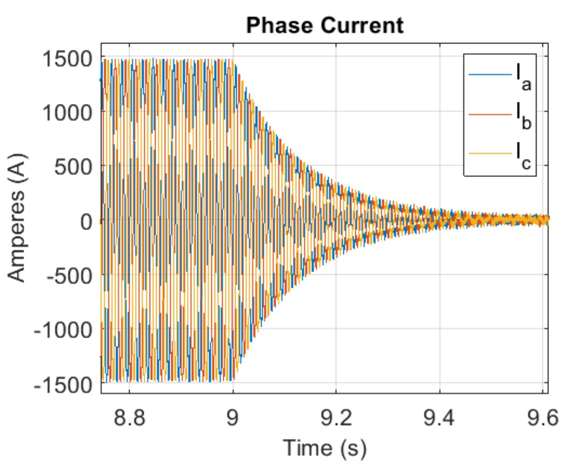


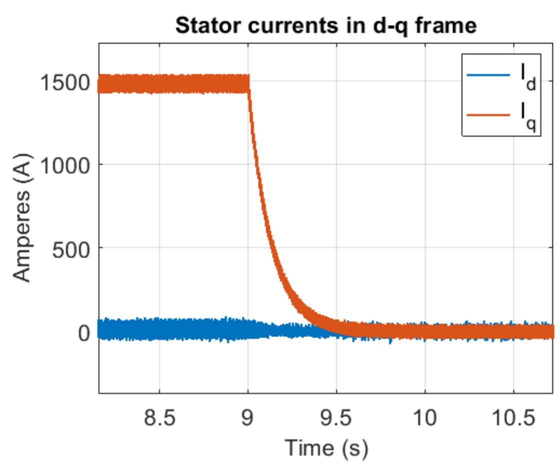
Figure 19: Torque vs time graph of the motor

In this part, we lower the mechanical torque to the zero as we operating in rated conditions. we expect our phase currents to decrease and of course the i_q current which deploys torque to decrease.

In the Fig. 20 below, we can observe the phase currents vs time



(a) Motor line currents during transient



(b) Motor stator d-q currents during transient

Figure 20: Line to line voltage general (a) and one cycle (b)

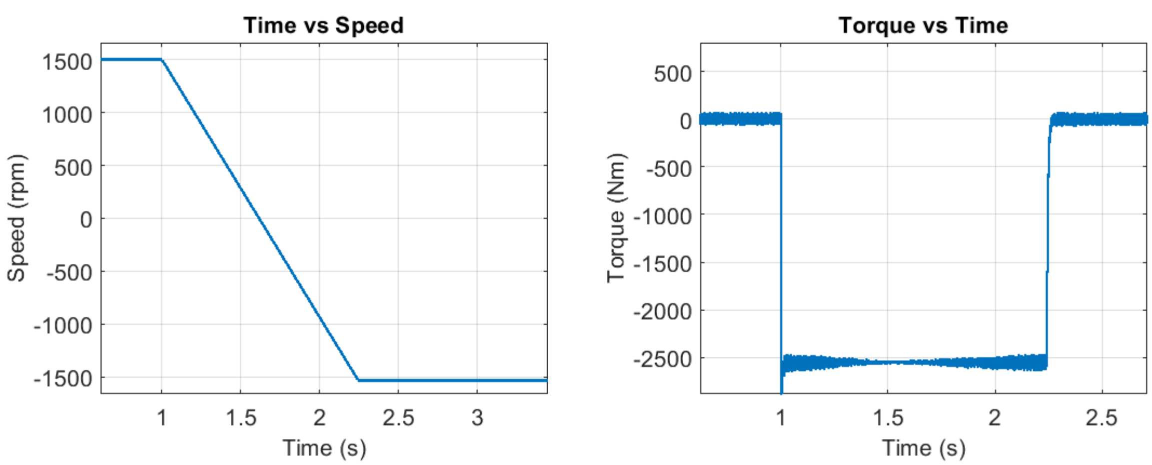
We can observe that the phase currents are lowering due to decrease in the torque. We know that the torque is directly proportional to the i_q current, and a decrease in the i_q while keeping i_d constant will decrease line currents. After the transient, we have a noise in the line currents due to the inertia of the motor and the noise in the controllers.

As we observe, the I_q current was it in rated value to apply rated torque at rated speed, then suddenly we decrease the load torque. Due to the controller, i_q current decreases to 0 where it provides zero torque, however, there are noise due to the controller circuit and motor itself.

3.1.3 Q1-3

We know that during the braking time, the motor supplies current to the utility side, and if we do not have a full quadrant operation or back to back rectifiers, it is not possible to supply energy from load to the grid. In this case of operation as we have in this project, it is not possible to have a current into the grid because of the diode rectifier. So, the solution must be braking resistance. During transient time, the energy stored on the load and the motor can be discharged through this resistor. It prevents the circuit from burn-outs and excessive heating. The braking resistance selection of us is $R = 0.5\Omega$

In the Fig. 21 we can observe that after we reverse the reference speed at time $t = 1$ the motor speed decreases to 0, and then reversely increases to its final value. Meanwhile, due to the reversal, a negative torque is applied to the motor and it creates a current in the negative direction. This current should be discharged in order to prevent burn outs in the circuitry. Because of this simple phenomenon we introduce a braking resistance to the circuit.

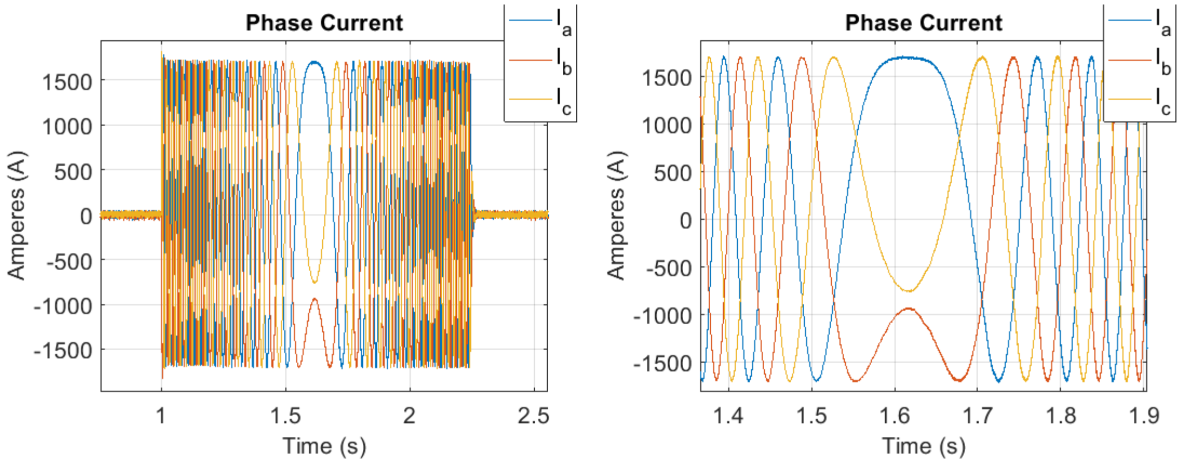


(a) Speed

(b) EM Torque

Figure 21: Reversal, speed vs time (a), electromechanical torque vs time (b)

In the Fig. 22 below, we can easily observe that at the steady state we have only noise in the line currents, then when we reverse the speed reference, current is produced in the motor in order to reverse the motor. It deploys power to the utility side as we discussed before. In the Fig. 22b we can see that the frequency of the current decreases to the zero and then increases again. This is due to the reducing speed of the motor and speeding up again.

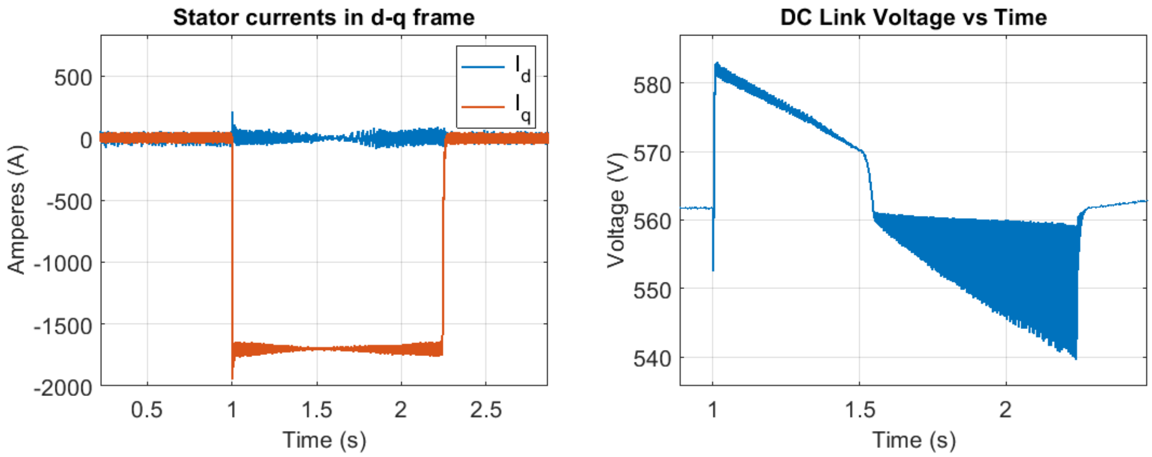


(a) Line currents during reversal

(b) Line currents during rotation direction change

Figure 22: Reversal, line currents

In the Fig. 23b below, we can see that our brake resistor starts operating voltage above 560, that is why in steady state we are constrained by 560V. Then, during the reversal due to the current supplied from the motor side, the voltage increases up to 580V, however, braking resistor allows us to discharge this energy. Then, the voltage is decreased to its final value after a transient period. When we have a look at Fig. 23a we can observe that in steady state both currents are zero with noise, however in the transient time, we have a negative i_q resulted from the motor's reversal. This current discharges over the braking resistance.



(a) Stator currents

(b) DC link voltage

Figure 23: Reversal, d-q currents (a) and DC Link voltage (b)

3.1.4 Q1-4

Now, we need to speed up the motor to the 150% rated speed. We need to control the current and voltage limits by doing so. First we need to fulfill the equation

$$i_{s,max} \geq i_d^2 + i_q^2 \tag{7}$$

and also:

$$V_{max} = \sqrt{(\omega_e \lambda + i_d \omega_e L_d)^2 + (i_q \omega_e L_q)^2)} \tag{8}$$

As we calculated from the previous part, the current i_q necessary for both operations is:

$$i_q = \frac{T_m}{3\lambda} \tag{9}$$

where Torque can be found as:

$$T = 1273Nm$$

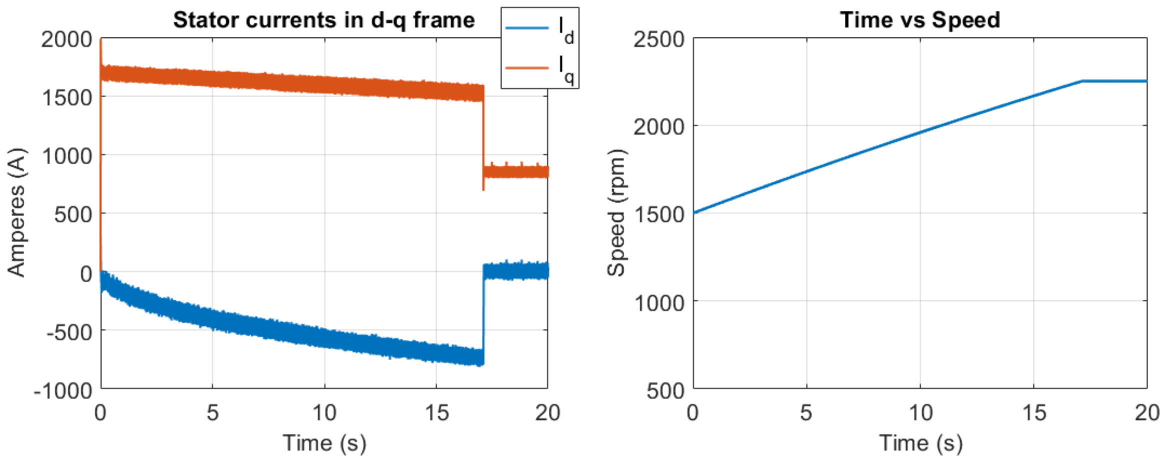
When we calculate it:

$$i_q = \frac{1273}{1.5} = 848.7A$$

In this case our $V_{max} = \dfrac{540}{\sqrt{3}} = 311V$ and we can calculate our minimum i_d using this equation. As we can see below:

$$311 = \sqrt{235.5 - 0.165 i_d)^2 + (140)^2)}$$

required $i_d = 0$. That means, we do not need to supply and i_d current to operate in this speed with half of the torque. Now, let us show this in simulation!



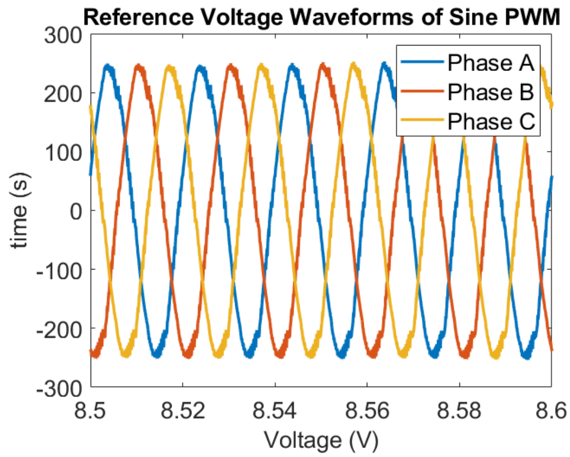
(a) Stator currents (b) Speed vs time

Figure 24: Field weakening, d-q currents (a) and speed vs time

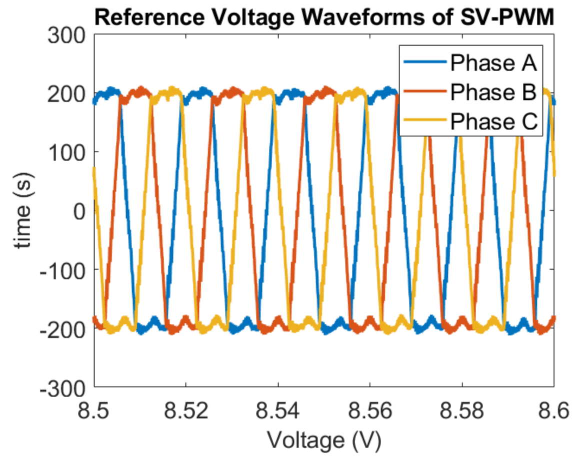
In the transient time, we need to apply the maximum i_q current to obtain a fast transient. We need as much as torque we can supply to the system. However, at the steady state when the motor reaches its final value, we do not have to supply same amount of i_q or i_d. As we can see from the Fig.24 above, it is possible to operate with zero i_d at that speed. It is possible because we are not operating in the maximum torque, and due to the SVPWM we have a larger margin for the field weakening!

3.2 Q2

In the Fig. 25 below we can observe reference voltages for SVPWM and SPWM at rated operation conditions.



(a) SPWM



(b) SVPWM

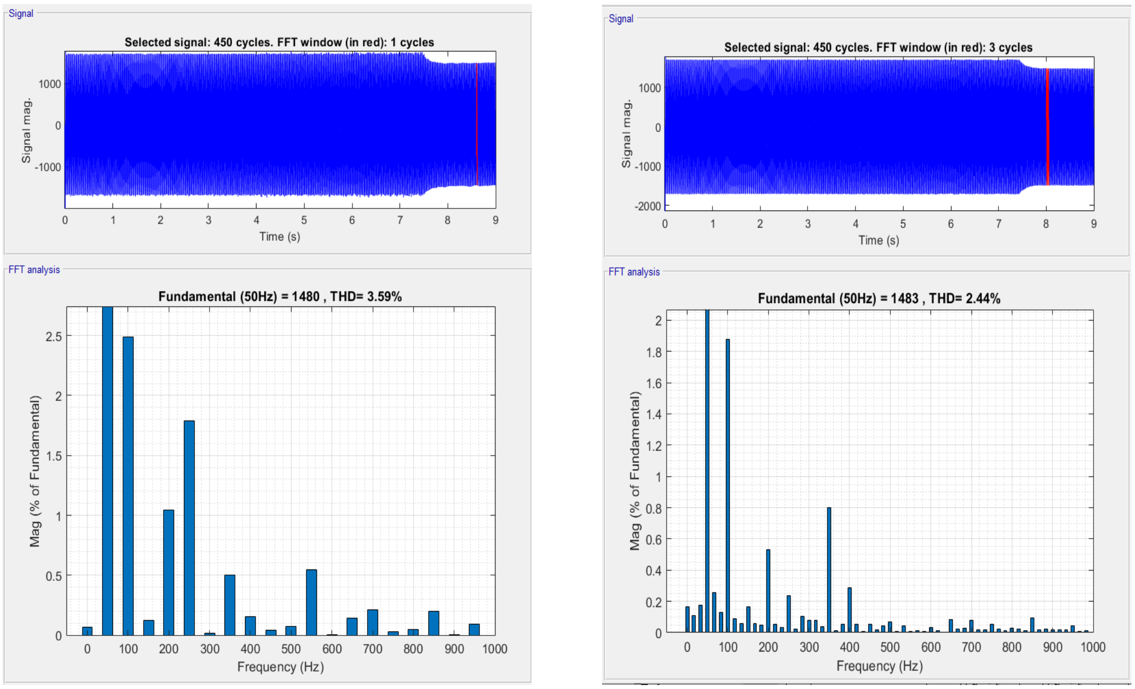
Figure 25: Voltage reference waveforms in three phase, SPWM (a) and SVPWM (b)

Reference voltages of SVPWM are different from reference voltages of SPWM. In SVPWM, duration times of V_7 and V_0 space vectors are equal, it means that both zero vectors are equal time applied to the circuitry, but in SPWM these durations are not equal and they are determined by analog comparators. This is the reason why two reference voltages are different. Moreover, we should notice that the total phase voltage of the SVPWM is much higher than the SPWM $V_{spwm} = \frac{V}{2}$ and $V_{svpwm} = \frac{V}{\sqrt{3}}$. This is due to the reference voltages and their durations. The above-mentioned phenomenon that zero vector durations are the same for SVPWM results in a higher phase voltage. That is why in high voltage applications SVPWM is the chosen one.

Above in the Fig. 25 we should also notice that both methods generate same current, however SVPWM has less peak in the voltage reference, which means it is possible to have larger voltages with SVPWM, where it is not possible for SPWM.

3.3 Q3

In the Fig. 26 below we can observe the THD analysis of SVPWM and SPWM methods.



(a) SPWM

(b) SVPWM

Figure 26: THD Analysis of both methods SPWM (a) and SVPWM (b)

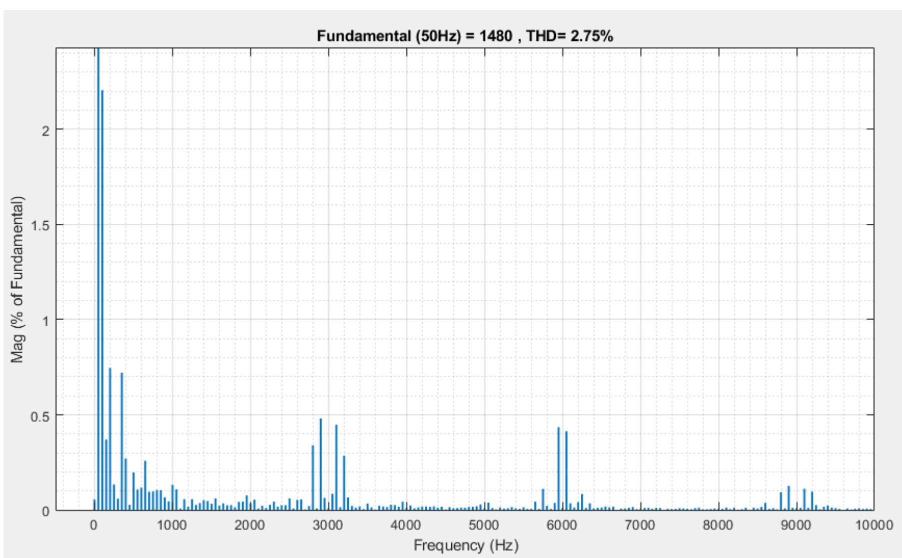


Figure 27: THD Analysis in switching frequencies

Above, we can see that SVPWM has 2.44% THD, and SPWM has 3.6% THD. From FFT analysis we can see that in both methods, there is no third harmonics due to the three phase inverter. Actually, we did not expect any harmonics around fundamental frequencies but due to the simulation and non-ideality of our PWM generation techniques, we have some harmonics around the fundamental frequency. Most importantly the THD values of both applications is very low. Also, this THD analysis is done in the rated current, which means it is done in the $m_a = 1$. If we are to decrease this value, then the THD of both line currents would be higher. Moreover, magnitudes of the harmonics are less in SVPWM comparing to the SPWM. Therefore, THD of SVPWM is less than SPWM. This means that SVPWM uses DC voltage with less harmonics, which means the power factor of SVPWM line current will be higher comparing to the SVPWM.

Also, it is essential to see that THD of SVPWM varies less comparing to the SPWM, in smaller ratios of m_a SPWM would show more harmonics, where SVPWM would show less.

When we look at the Fig. 27 we can see that around the f_s and its multiples we can see harmonics. These harmonics are determined by the modulation ratio, and unipolar switching characteristics. We can see that since we are applying a unipolar switching strategy, the harmonics are very very low, and it effects total harmonics a very little value!

3.4 Q4

For high performance drive, SVPWM is better choice.

- Firstly, it has less switching losses because when the voltage changes, only one switch changes its states. In SPWM this is not the case, and multiple switchings cause higher losses on the switches.
- Another advantage of SVPWM is that is uses less DC voltage to reach same line-to-line voltage, this is due to harmonics of the both application methods. SVPWM is better in harmonics.
- In high voltage applications, SVPWM is more advantageous due to its high voltage capability. It caries almost 15% more voltage than the SPWM in applications and when we think of applications in kV range, this means a lot.

The reasons itemized above shows that SVPWM is a better choice for high performance applications, its digital nature and hand made zero vector selections makes it a better choice against the SPWM method. However, the necessity of a digital controller and the effort to implement it is higher than the SPWM. In this project, it was very hard to implement SVPWM where SPWM was very easy to implement at all.