**MIDDLE EAST TECHNICAL UNIVERSITY**
**ELECTRICAL AND ELECTRONICS ENGINEERING DEPARTMENT**

**EE462 UTILIZATION OF ELECTRICAL ENERGY**
**EE464 STATIC POWER CONVERSION – II**
**SOFTWARE PROJECT**
**REPORT**

# Design of a SM-PMSM Variable Frequency Drive with Matlab/Simulink

**Due Date: 02.06.2019**

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| | |
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# 1. INTRODUCTION

In this project, we are asked to design a SM-PMSM Variable Frequency Drive using Matlab/Simulink. The available supply is a three-phase AC source (50 Hz, 400Vl-l) and the PM is a surface-mount motor.

The motor ratings of the surface mount PM synchronous machine (SM-PMSM);

- $Pnominal$=80 $kW$
- $Tnominal$=300 $Nm$
- $nmax$ =7000 $rpm$
- Pole number: p=8
- $Flux\ linkage$: $\lambda PM$= 0.2 Vs (Wb-t)
- $Ld$=$Lq$= 500 μH
- $Inominal$= 250 $A$ (peak)
- Phase resistance: $Rs$=50 mOhm
- Equivalent inertia of the system: $Jeq$= 10 kg m2

3-phase full-bridge diode rectifier is connected to the grid. The 3-phase motor drive inverter is connected to the diode rectifier as shown in Figure 1.

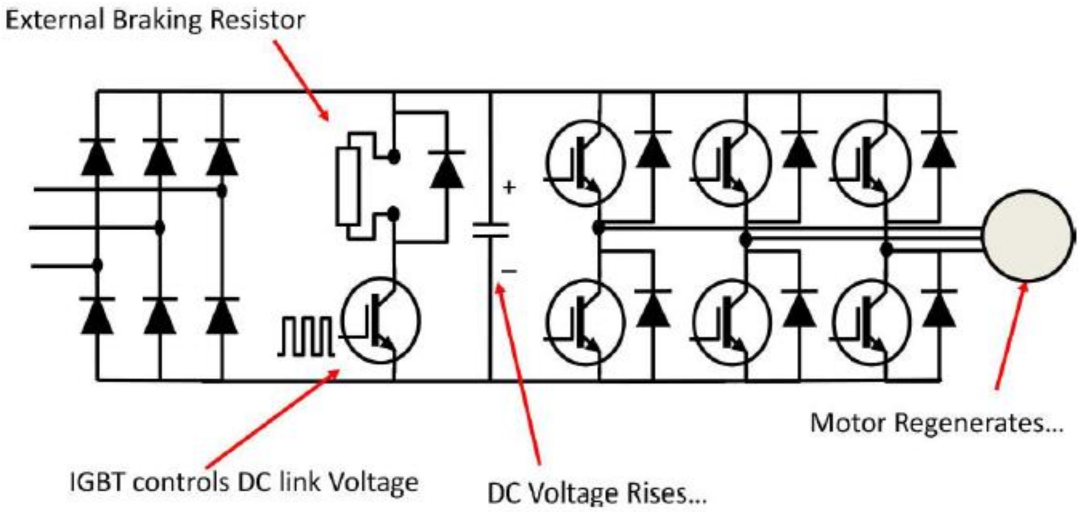



*Figure 1: The model used in overall schematic of the Motor Drive in Open-Loop configuration*

Starting with pre-design, rated values are to be calculated. Then, a suitable DC-Link capacitor is chosen according to created Simulink model illustrated in Figure 3.

Later on, Sinusoidal PWM method with current and speed controller using id-iq parameters are implemented with our own designed Clarke-Park transformation subcircuits. Then, some analysis using the data obtained from Voltage, Current, Speed etc. are performed. In these analysis, different load-characteristics and speed requirements are implemented.

After finishing the Sinusoidal PWM analysis, Space Vector PWM method is applied with readily available blocks. Then, 2 methods are compared and differences are discussed.

Finally, component selection and verification part is finished. Designed system is realized using the commercially available components. While choosing the components, application notes are used heavily. The characteristics for each component are analyzed and components are chosen accordingly. Efficiency is calculated and the drive is completed.

## 2. PART A: Pre-design Stage

1. Rated torque of the motor is $T_{nominal}$, 300Nm. Rated speed of the motor is found by (1) and (2).

$$P_{nominal} = T_{nominal} * \omega_m \quad (1)$$

$$\omega_m = \frac{P_{nominal}}{T_{nominal}} = \frac{80000}{300} = 266.67\ \frac{rad}{s} \quad (2)$$

2. The maximum applied electrical frequency is found by (3).

$$f_e = \frac{n_{max}}{60} * pp = \frac{7000}{60} * 4 = 466.67\ Hz \quad (3)$$

In LV applications where the inverter output is in between 380-460$V_{rms}$, IGBT voltage class in low-level inverter topology is 1200V. In Figure A.1, total semiconductor losses as a function of carrier frequency can be seen. [1]. Choosing FF200R12KS4 as our IGBT and 2000W as a reasonable loss we decided to use 5000Hz. In this case $m_f$ is given by (4). Since we are operating below $m_f$ =21, $m_f$ should be an odd integer. To have $m_f$ approximately equal to 11, we chose $f_s$ as **5130Hz.**

$$m_f = \frac{5000}{466.67} = 10.71 \quad (4)$$

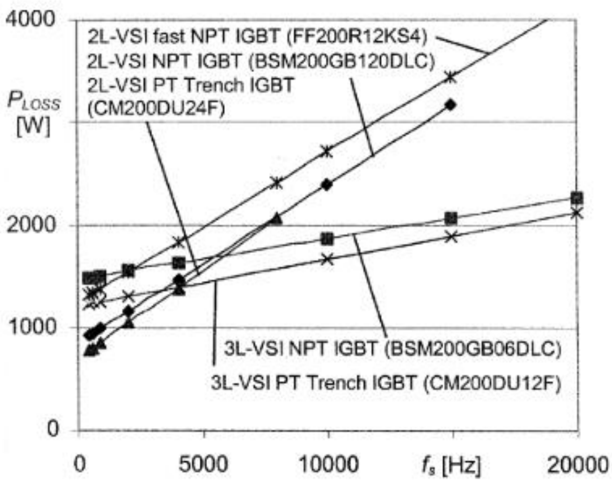



*Figure 2: Total semiconductor loss as a function of carrier frequency*

3. In this part we are required to find the suitable DC link capacitor for the rectifier output so that the DC input of the inverter will be 540V. Equivalent resistance at the rated current is 2.16Ω. The rectifying circuit and voltage output waveform can be seen in Figure A.2 and 3, respectively. DC link capacitor is 1mF as it can be seen output voltage is oscillating around 540V. However, 1mF is already is a big value.

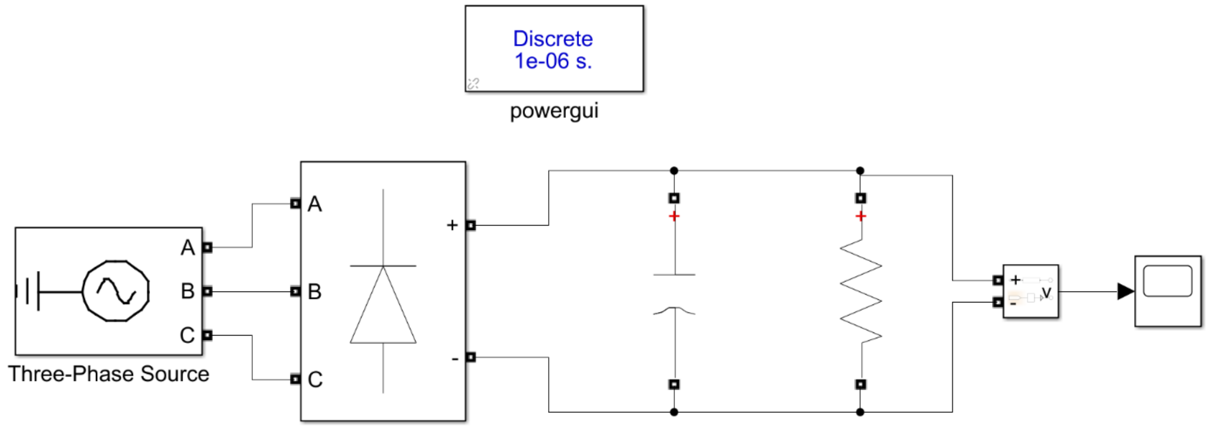



*Figure 3: Simulink circuit of the rectifier*

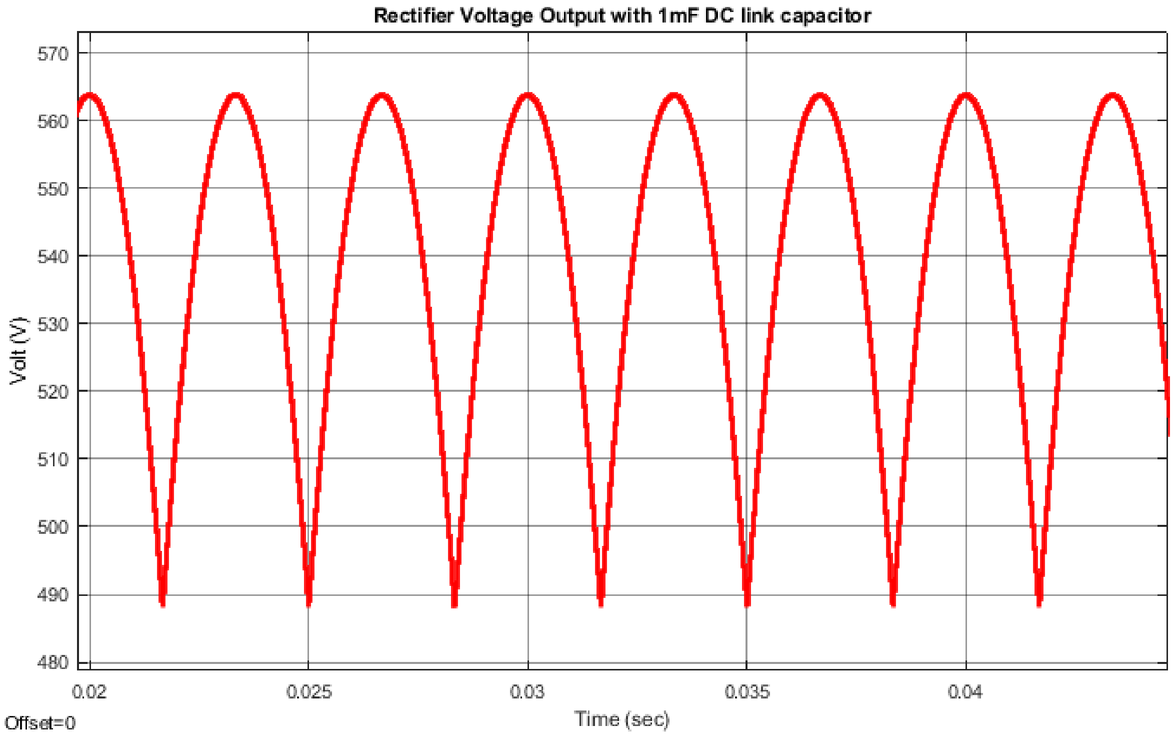



*Figure 4: Output voltage of the rectifying unit*

# 3. PART B: Sinusoidal PWM

In this part, we are asked to implement a SMPMSM motor drive using sinusoidal PWM scheme. The controller must adjust the rotor speed according to the reference value and set a current limit to the nominal value using id, iq parameters. This motor drive can be seen in Figure B.1. Subsystem details in the given Simulink model can be observed in the slx. files uploaded to ODTUClass.

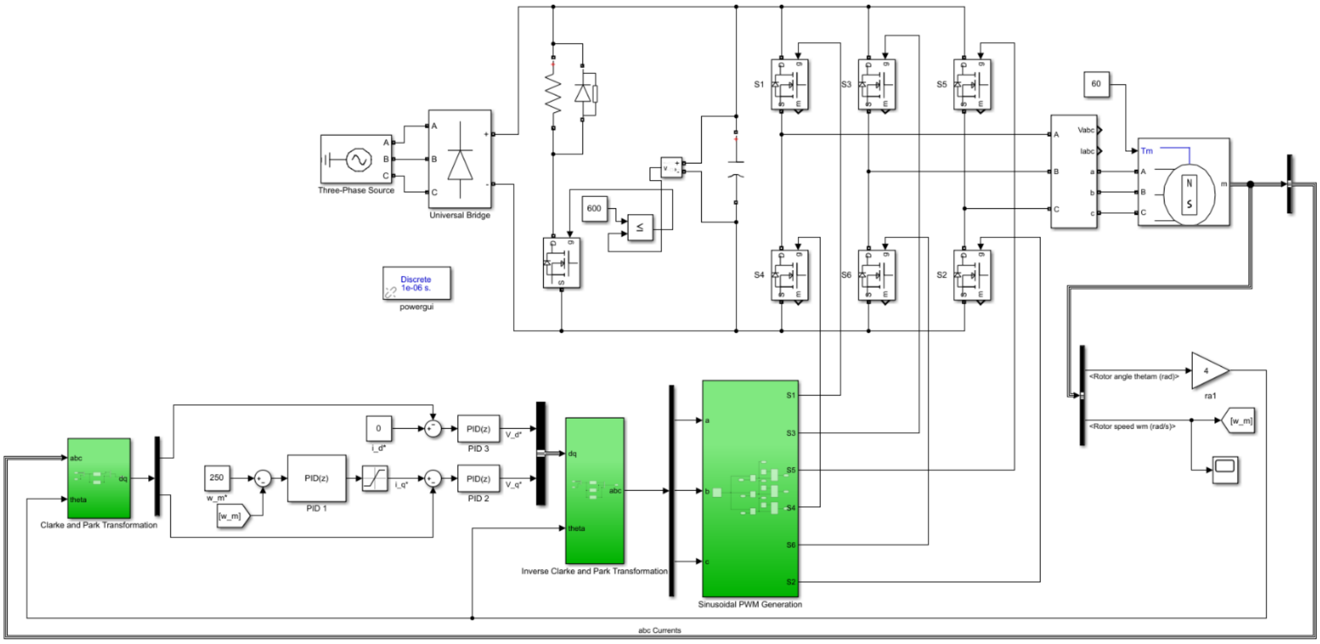



*Figure 5: Detailed Simulink model of the SPWM motor drive*

1. %90 of the rated speed is found using the equation (5).

$$\omega_{nominal} * \%90 = 266.67 \ \frac{rad}{s} * \%90 = 240 \ \frac{rad}{s} \quad (5)$$

Now, apply the %90 rated speed to rated speed at rated current while driving a constant torque load of 60Nm.

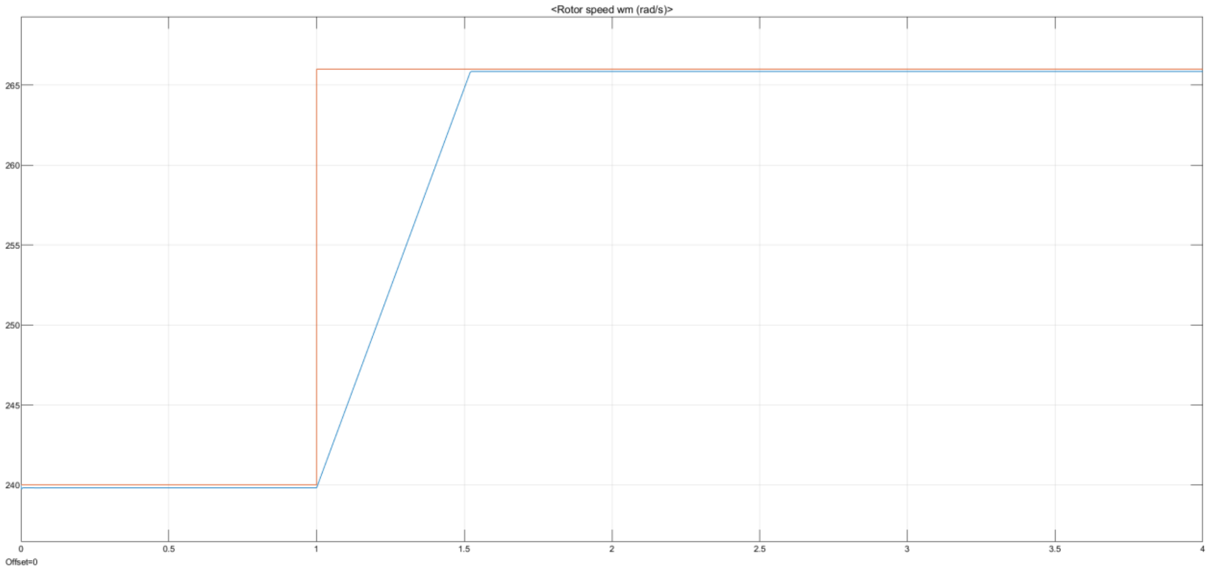



*Figure 6: Applied input and Speed vs Time plot*

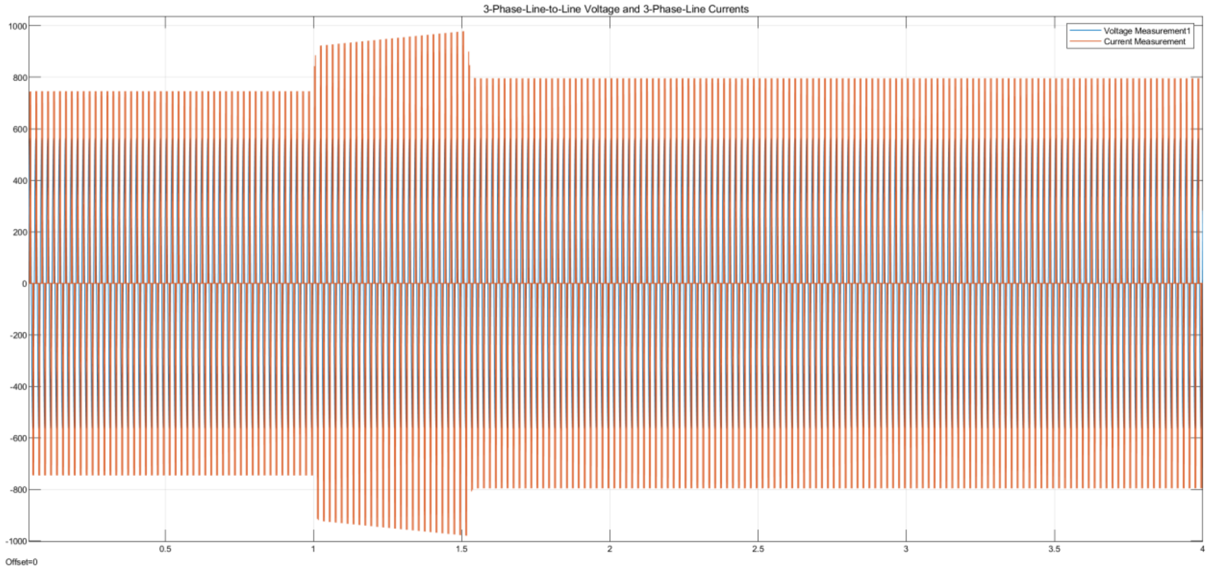



*Figure 7: 3-phase line-to-line voltages and currents vs time plot*

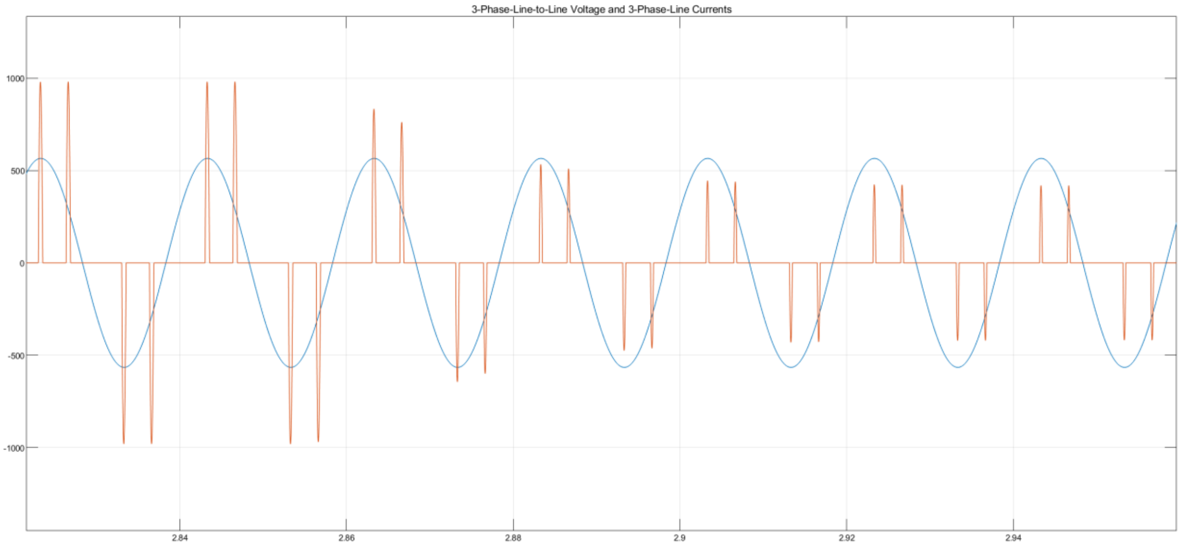



*Figure 8: 3-phase line-to-line voltages and currents vs time plot zoomed in*

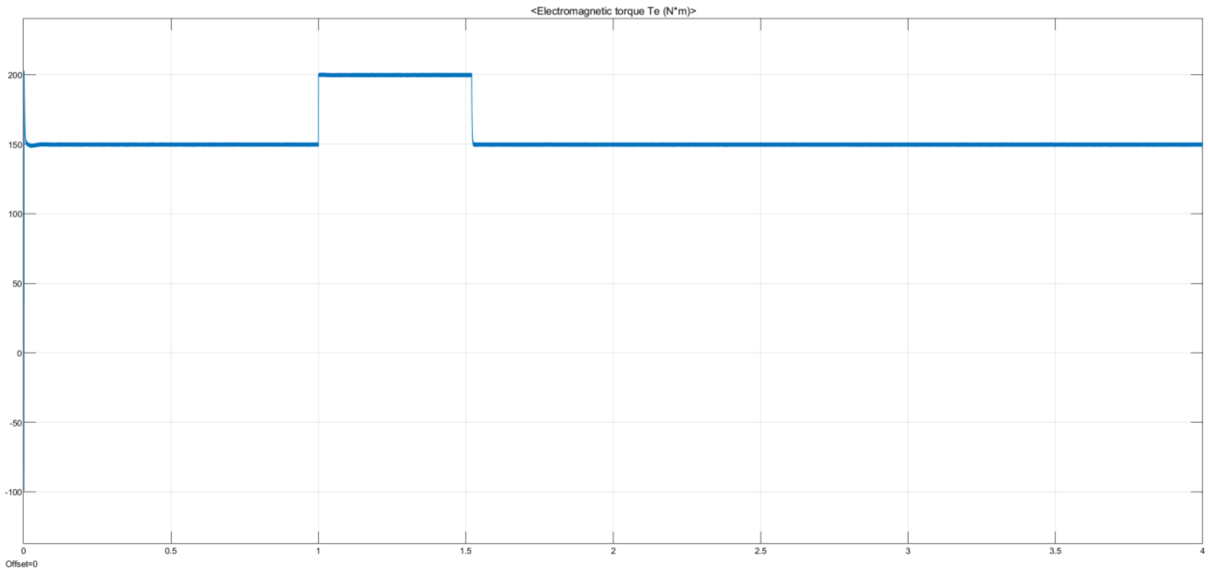



*Figure 9: Torque vs time plot*

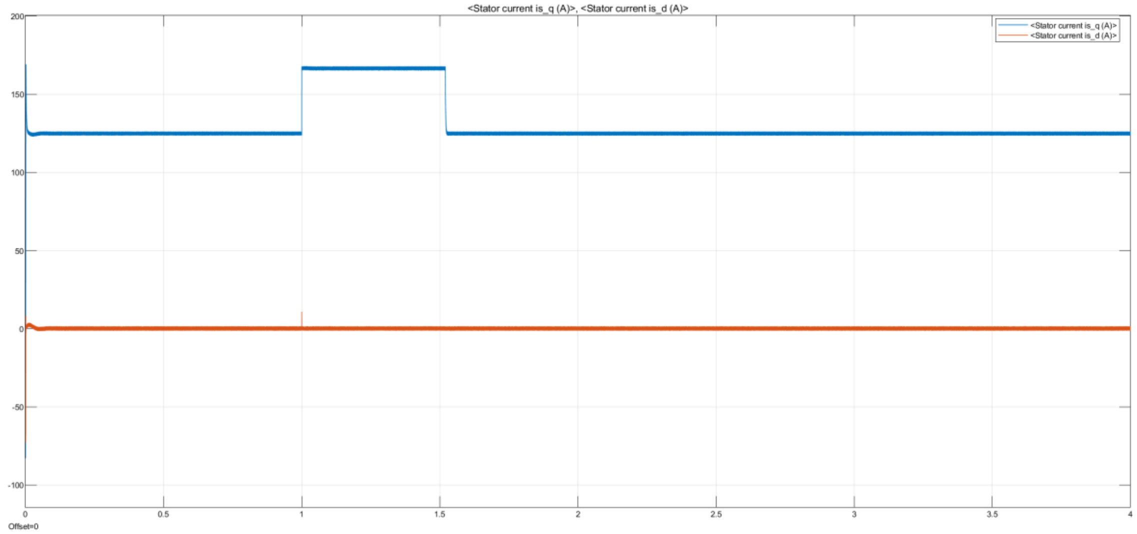



*Figure 10: d and q currents of the motor*

**Comments:**

- As shown in Figure 6, speed is increased to rated value with a unit step increase. In about 0.5sec, drive response reaches to its steady-state value.
- In the transient time, drive system applies more motor torque than steady-state torque value to reach rated speed in the smallest time period. In order to apply more torque, more line currents are drawn from the grid as shown in Figure 7 and zoomed in version Figure 8. The currents have high ripples and note that it is not a desired waveform for THD and harmonics.
- In Figure 9, the torque increase is depicted. Note that the torque component is proportional to q currents. This relation is illustrated in Figure 9&10.

2. Speed reference is set to 266 rad/sec.

First, the load torque is reduced from 150Nm to 0Nm at time = 1sec. Then, the load torque is kept constant at 0Nm. The resultant speed-time graph is depicted in Figure 11.

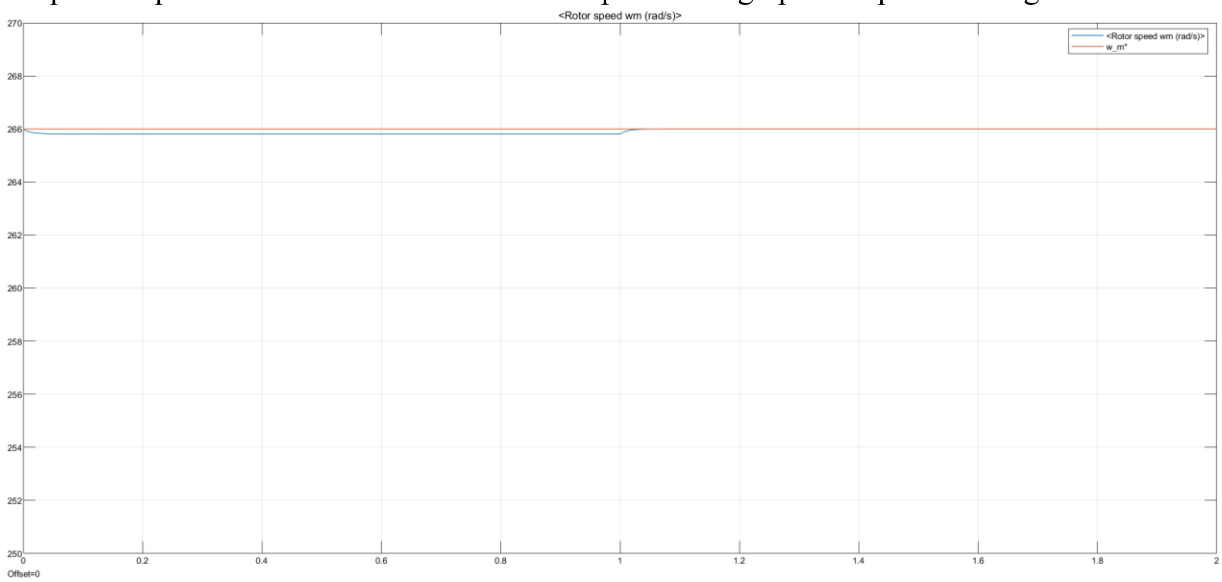



*Figure 11: Speed vs time plot with torque load 150Nm to 0Nm*

Then, the load torque is reduced from 250Nm to 0Nm at time = 1sec. Then, the load torque is kept constant again at 0Nm. The resultant speed-time graph is depicted in Figure 12.

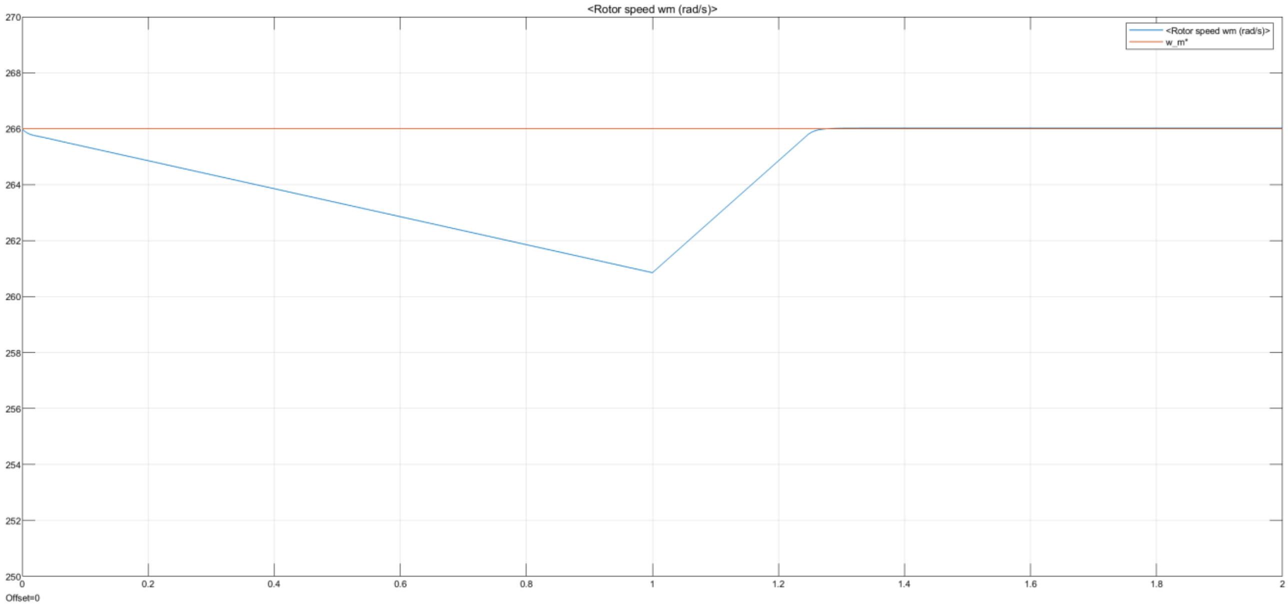



*Figure 12: Speed vs time plot with torque load 250Nm to 0Nm*

Later on, the load torque is reduced from 300Nm to 0Nm at time = 1sec. Then, the load torque is kept constant again at 0Nm. The resultant speed-time graph is depicted in Figure 13.

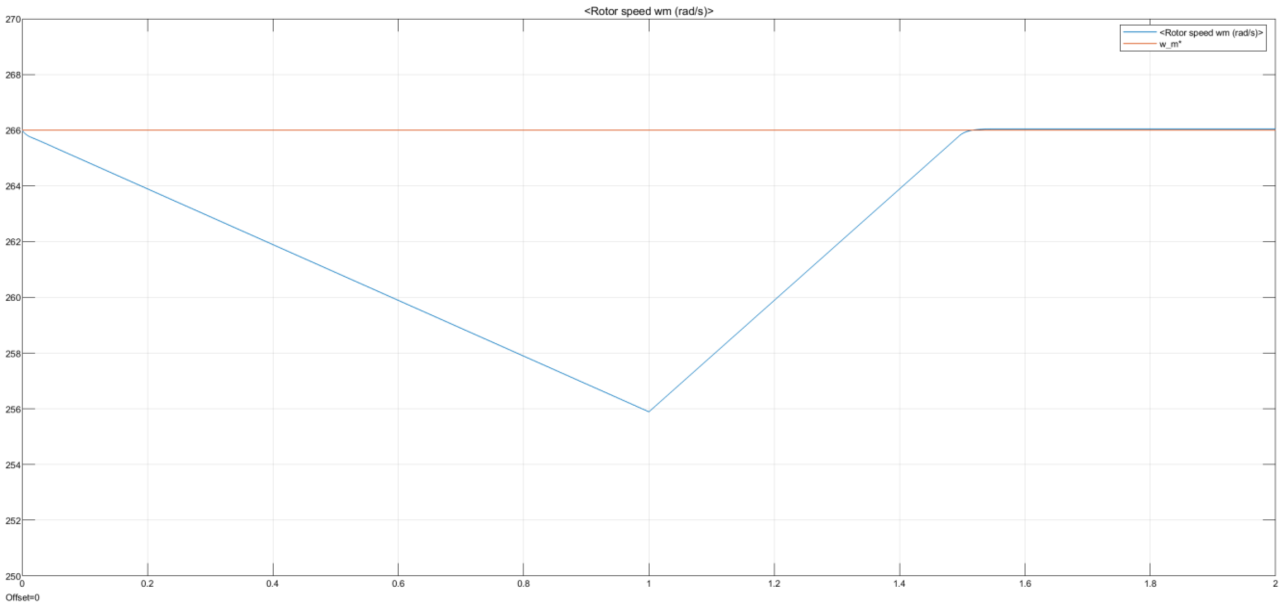



*Figure 13: Speed vs time plot with torque load 300Nm to 0Nm*

Finally, the load torque is reduced from 75Nm to 0Nm at time = 1sec. Then, the load torque is kept constant again at 0Nm. The resultant speed-time graph is depicted in Figure 14.

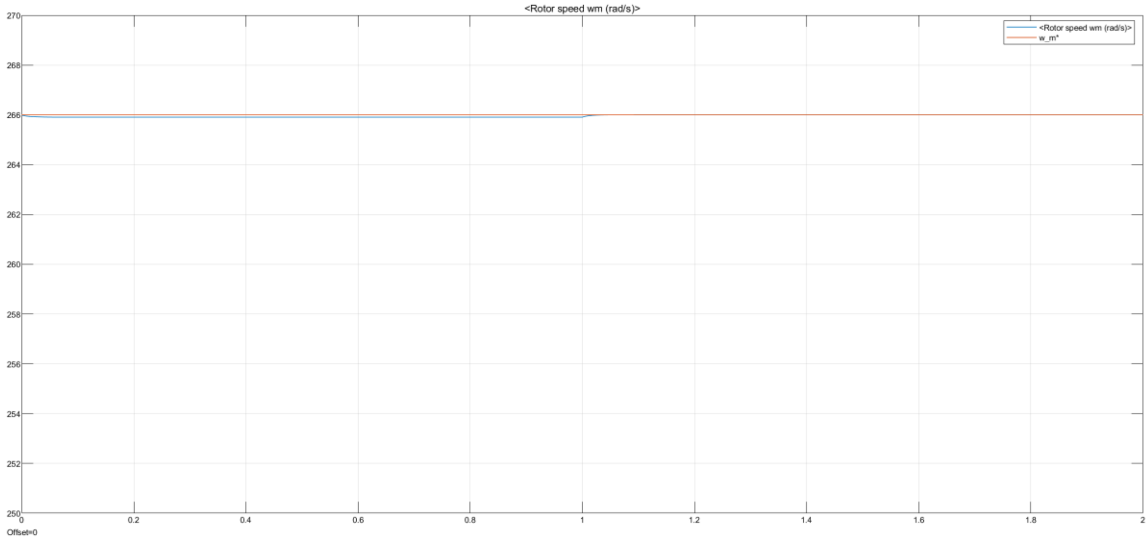



*Figure 14: Speed vs time plot with torque load 75Nm to 0Nm*

**Comments:**

- Considering Figures 11 to 14, when the load torque gets bigger initially, the response to change to no load becomes slower. This is because the machine tries to handle higher load torques. When the load torque is higher, the current and applied torque to the output from inverter becomes much higher. Hence, the response becomes slower as the control system gives commands accordingly to reduce more currents and torque values for no load operation.
- Also, considering mechanical situation, it is hard to stabilize the system with higher load torques compared with light loads due to high inertia of the machine. As a result, the drive performance is better with light loads, but it is still working with nominal torque values with a slower response to changes.

3. Firstly, braking resistor is not implemented to the system. Note that in other parts, it is included into the system for correct operation of the drive system.

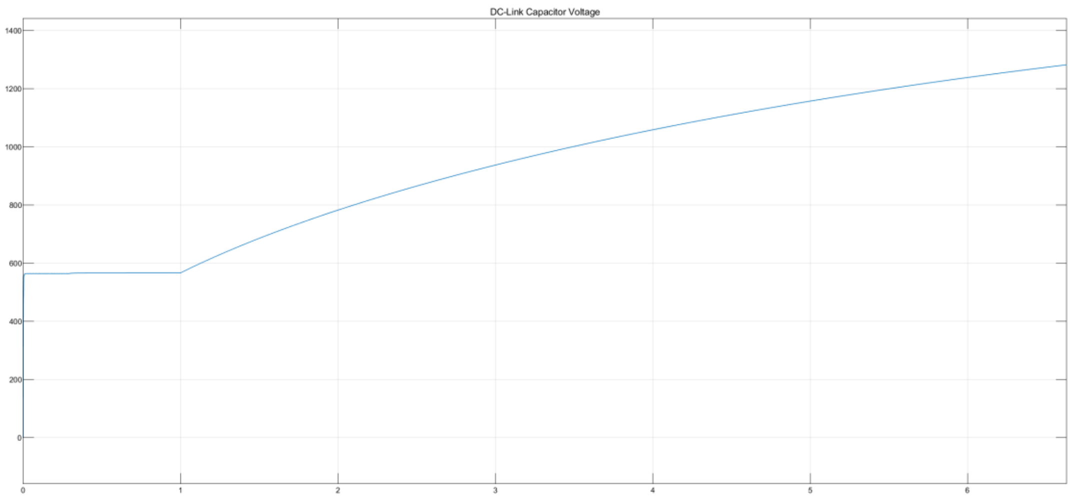



*Figure 15: DC-Link Capacitor Voltage waveform*

As seen in Figure 15, DC-Link capacitor voltage exceeds 600V while trying to reverse the speed. It is because system tends to operate in generating mode. However, 3-Phase rectifier blocks current to flow through source. Hence, capacitor voltage increases incredibly. Therefore, a braking resistor is implemented. **Operation is not feasible.**

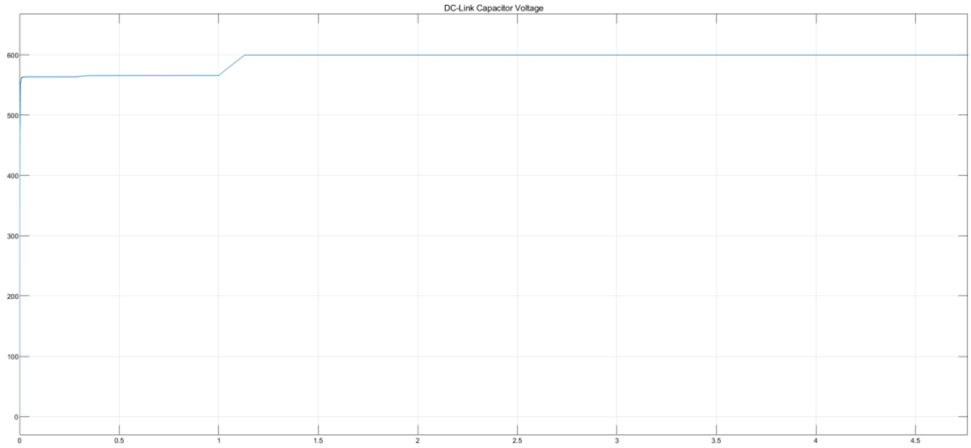



*Figure 16: DC-Link Capacitor Voltage waveform with braking resistor implemented*

In Figure 16, the ‘chopped’ DC-Link Capacitor voltage waveform is obtained. The voltage is saturated at 600V which is the maximum DC-Link voltage desired. Now, operation becomes feasible.

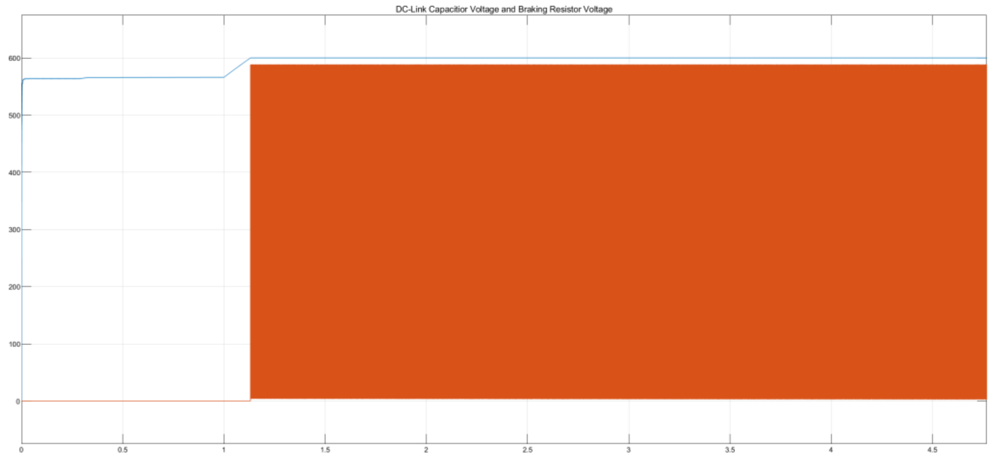



*Figure 17: Voltages on DC-Link Capacitor and braking resistor*

As seen in Figure 17, when the voltage tries to exceed 600V, braking resistor system is activated and the voltage is dissipated on it.

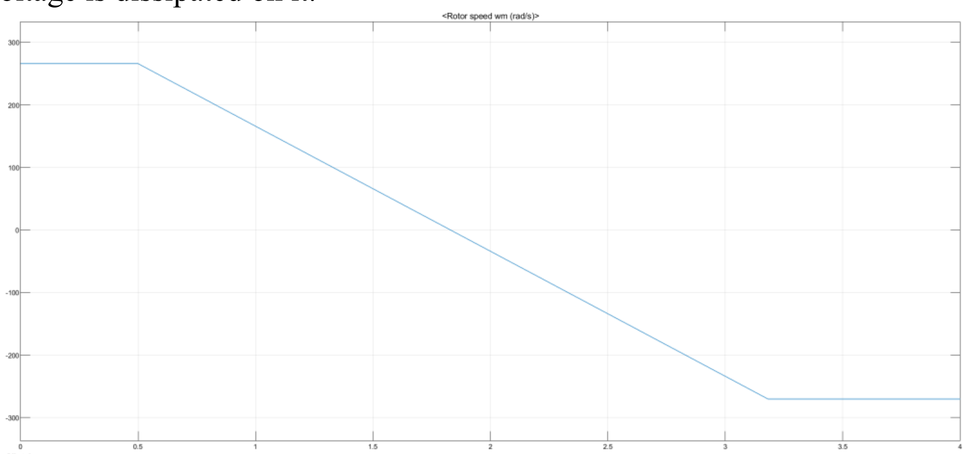



*Figure 18: Speed vs time plot*

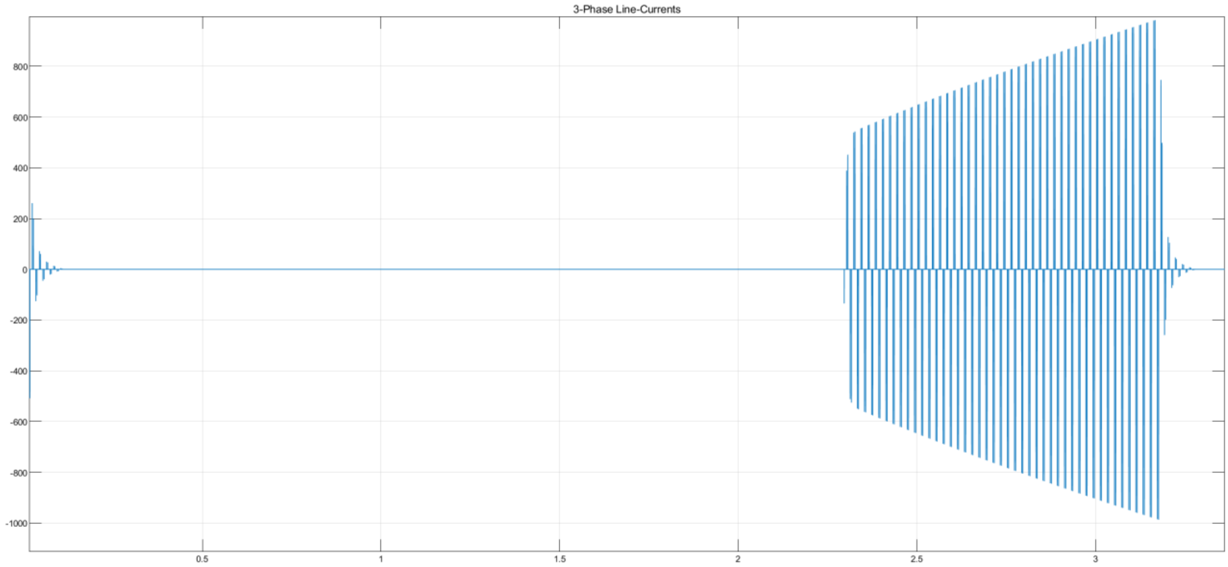



*Figure 19: 3-Phase Line currents during speed reversal*

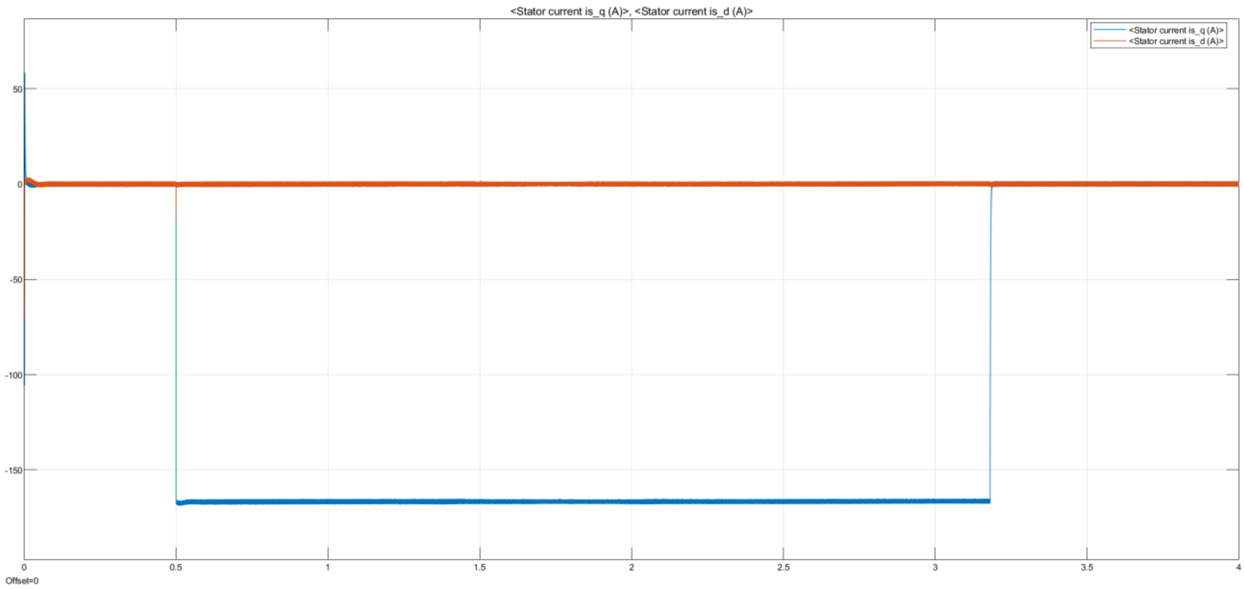



*Figure 20: d and q currents*

**Comments:**

- In Figure 18, the response when the reference is changed to negative rated speed. Drive system handles this change with breaking resistor in about 3.1 seconds which shows that drive system is capable of giving fast responses to this sudden changes.
- In Figure 19, line currents drawn from the grid is illustrated. Actually, it is not a waveform we desire in a drive system as it includes too much ripples which are more than rated value that our motor is capable of handling. However, the currents are transient. The important thing is to select power semiconductors which are durable with these peak values. Otherwise, the peaks may damage the system.
- As it is known the q currents are the torque components, a negative current is applied which results in negative torque to reach negative rated speed. It is applied until the system reaches to steady state operation. d currents are zero as expected since we are not operating in field weakening region.

4. Having half of the rated torque at rated speed, in order to increase speed to %150 of the rated speed, field weakening should be applied. Otherwise, the current drawn by the motor exceeds the rated current as power should be conserved. In base speed range, Id=0 and Iq>0. In field weakening region, Id<0 and Iq>0. Therefore, a negative d current should be applied to the system.

$$T = \frac{3}{2} * pp * \lambda_{pm} * i_q \quad (6)$$

For SM-PMSM, torque is found using the equation (6). Inserting values, T=150Nm and motor parameters given;

$$i_q = 125A \quad (7)$$

Now, $i_d$ can be found using the equation (8) where $i_{max}$ is equal to 250A.

$$i_{max} = \sqrt{{i_d}^2 + {i_q}^2} \quad (8)$$

$$i_d = 216.5A \; (in\ negative\ direction) \quad (9)$$

## 4. PART C: Space Vector PWM (SVPWM)

Since in this part we are allowed to use readily available Simulink blocks implementing SVPWM is quite easy. Without changing control loops, SVPWM Generator (2-level) block, which can be seen in Figure 21, is added which uses inverse Clarke's transformation instead of Sinusoidal PWM Generator. Also, the inverter is replaced with readily available 3-phase inverter block.

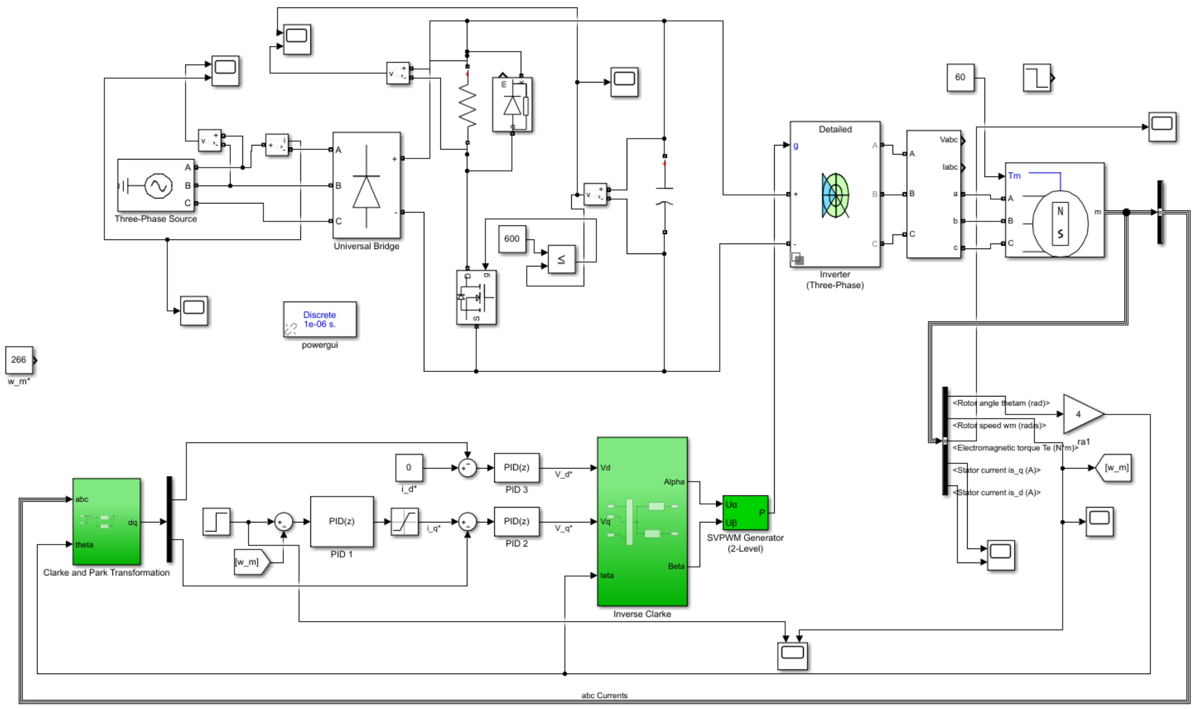



*Figure 21: SVPWM Simulink model implemented system*

**1.** In this part, we are asked to repeat part B using a Space Vector PWM algorithm.

1. All steps are repeated without explanation in this part. Only comments are included.

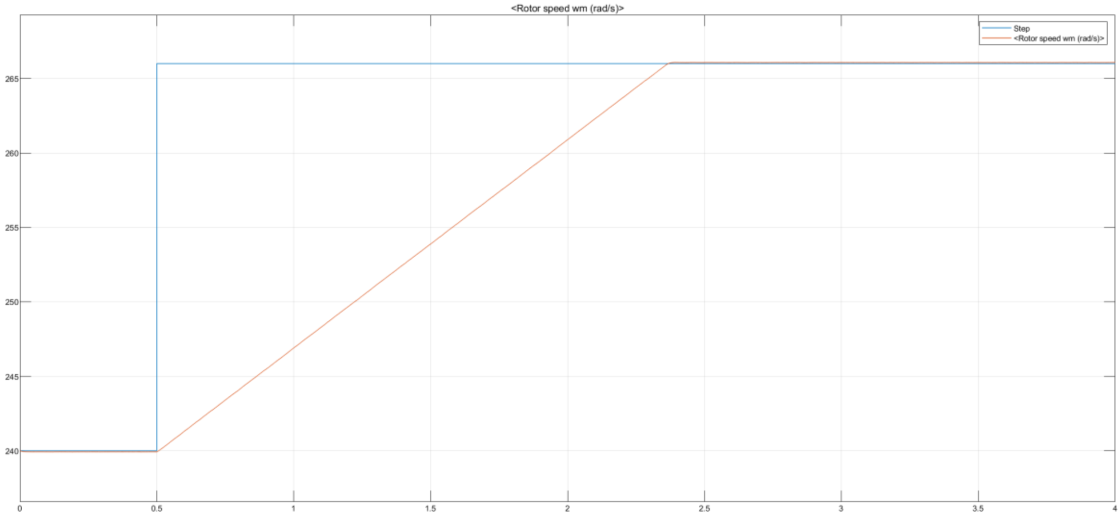



*Figure 22: Applied input and Speed vs Time plot*

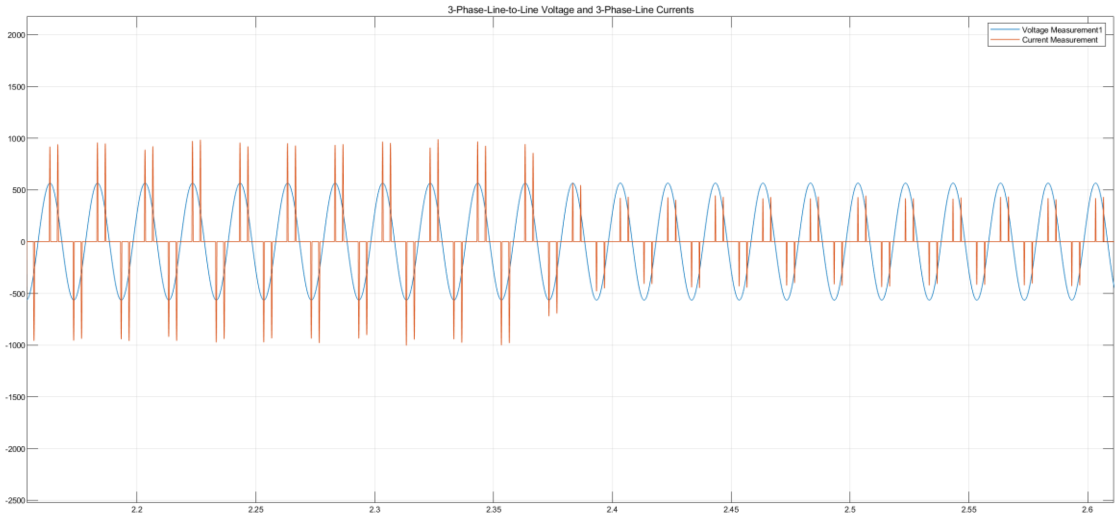



*Figure 23: 3-phase line-to-line voltages and currents vs time plot*

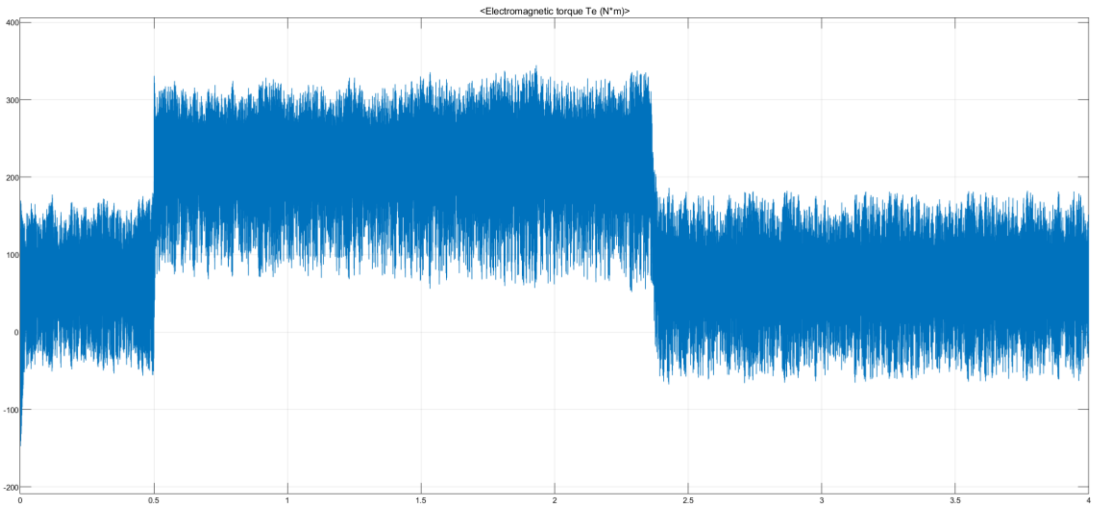



*Figure 24: Torque vs time plot*

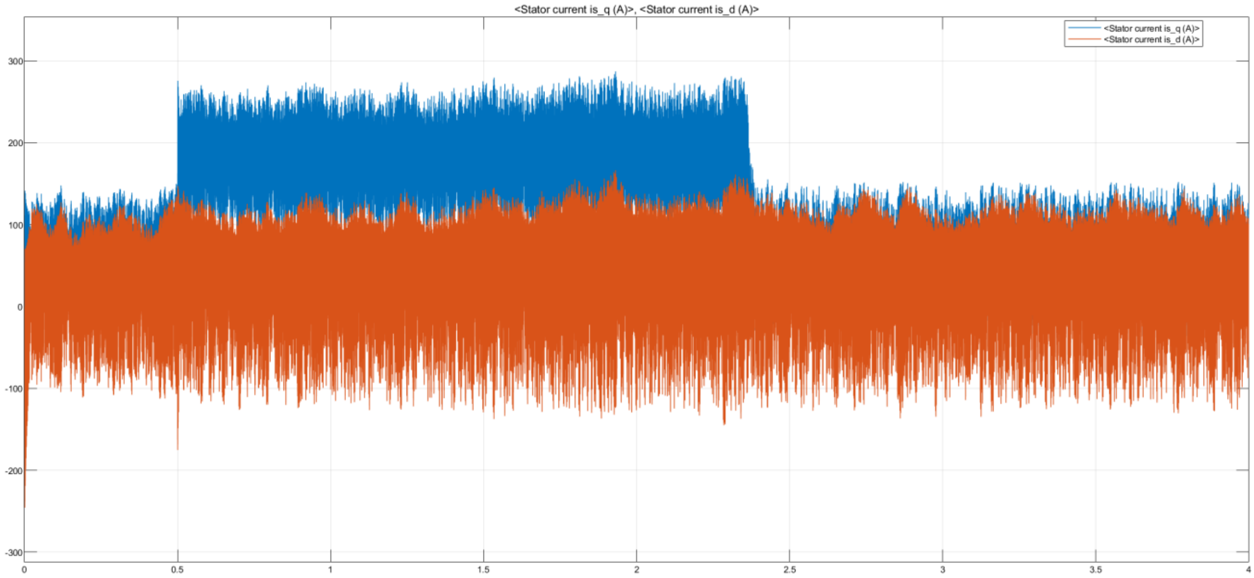



*Figure 25: d and q currents vs time plot*

**Comments:**

Looking to Figures 22 and 23, system responses are as expected. However, in torque and d-q current plots, too much oscillations are observed. Hence, the real-time implementation of this simulation does not seem to be realistic. As a result, the analysis are not completed with SV-PWM.

**2.** The main differences between SPWM and SVPWM are listed below.

- SVPWM has a better performance due to less THD, greater PF and less switching losses because SVPWM utilizes advance computational switching technique to reduce THD.

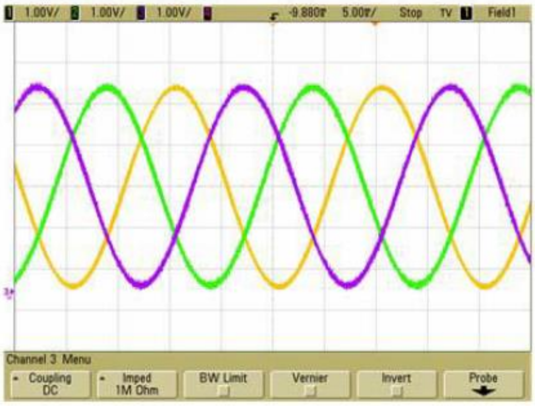
- SVPWM reduces switching losses because of the changing of any one switching state which results in one single phase voltage change every time.

- Sine-PWM and the usually applied SV-PWM have the same sequences. The difference is the timings of zero-states. In SV-PWM, zero vector timings are equal to each other. In Sine PWM, it is not an obligation.

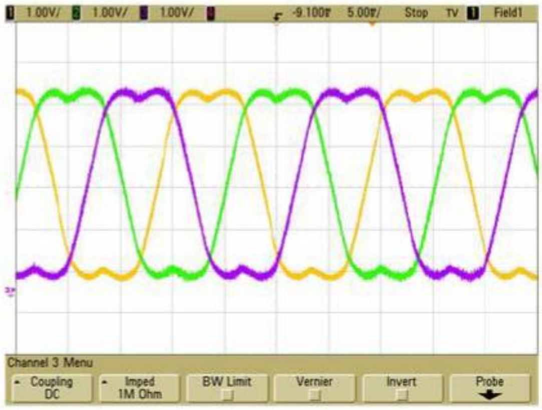
- SV-PWM gives output with $V_{phase} = Vdc/\sqrt{3}$
  Sine-PWM gives output with $V_{phase} = Vdc/2$

  As a result, for high voltage required operations, SV-PWM gives much more voltage and the operation range is increased in SV-PWM modulation. Therefore, for high performance drive, SV-PWM technique would be preferred.

**3.** For rated voltages, we expect the reference voltage waveforms as shown in Figure 26.




3-phase reference voltages with Sine-PWM




3-phase reference voltages with SV-PWM

*Figure 26: Reference voltages for Sine-PWM and SV-PWM*

In simulation of SV-PWM, the results are not obtained properly. Thus, expected waveforms are illustrated. The difference is due to usage of zero vectors. In SV-PWM, zero vectors are used more efficiently. Hence, the voltage rms values are much higher than Sine-PWM.

**4.** As we are not able to simulate the SV-PWM, an online research is performed for discussing FFT analysis for both methods. In a research article found online [1],

The SPWM and SVPWM techniques used to switch voltage source inverters are compared in terms of THD. When the THD value of these voltages and currents are analyzed, SVPWM technique has been found to be a more efficient switching method in terms of power quality.

Considering the other researches, we expect in SVPWM technique, THD is less and operation freqency spectrum is much higher than Sine PWM method.

# 5. PART D: Component selection and verification

**Power Semiconductor Selection:**

According to [2] when the inverter output is in between 380-460$V_{rms}$, IGBT voltage class in low-level inverter topology should be 1200V. The current passing through one of the switches, S1, can be seen in Figure 27. Then, the switches and diodes should at least be capable of carrying 50A.

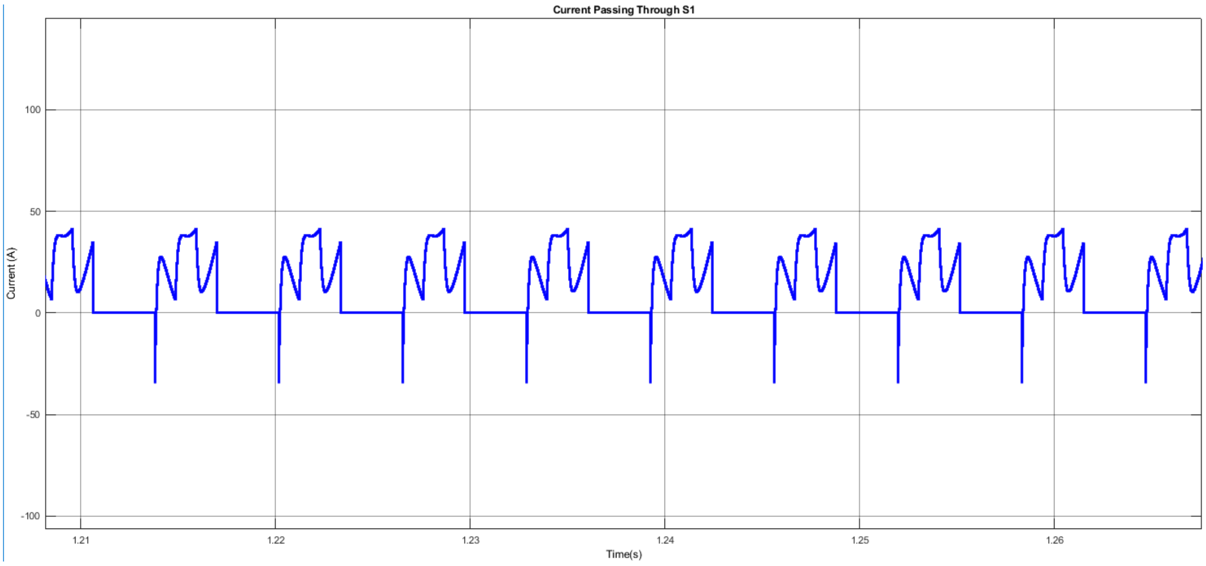


*Figure 27: Current on S1*

We chose IRF9540 which is a fast switching Mosfet, whose datasheet is given by [3]. Its maximum rated values can be seen in Figure 28.

| PRODUCT SUMMARY | | |
|---|---|---|
| $V_{DS}$ (V) | - 100 | |
| $R_{DS(on)}$ ($\Omega$) | $V_{GS}$ = - 10 V | 0.20 |
| $Q_g$ (Max.) (nC) | 61 | |
| $Q_{gs}$ (nC) | 14 | |
| $Q_{gd}$ (nC) | 29 | |
| Configuration | Single | |

*Figure 28:Maximum rated values of the MOSFET*

Diodes in the three-phase inverter should have the same ratings as well. We chose QR_1230R30 which is a fast switching diode, whose datasheet is given by [4]. Its maximum rated values can be seen in Figure 29.

**Absolute Maximum Ratings, $T_j$ = 25 °C unless otherwise specified**

| Ratings | Symbol | QRD1230R30 QRC1230R30 QRF1230R30 QRJ1230R30 | Units |
|---|---|---|---|
| Repetitive Peak Reverse Blocking Voltage | $V_{RRM}$ | 1200 | Volts |
| Non-Repetitive Peak Reverse Blocking Voltage | $V_{RSM}$ | $V_{RRM}$ + 100 | Volts |
| DC Current, $T_C$ = 80°C (Resistive Load) | $I_{F(DC)}$ | 210 | Amperes |
| Peak Half Cycle Non-repetitive Surge Current (t = 8.3mS, 100% $V_{RRM}$ Reapplied) | $I_{FSM}$ | 2550 | Amperes |
| $I^2t$ for Fusing for One Cycle (t = 8.3mS, 100% $V_{RRM}$ Reapplied) | $I^2t$ | 27,000 | $A^2$sec |
| Operating Junction Temperature | $T_j$ | -40 to 150 | °C |
| Storage Temperature | $T_{stg}$ | -40 to 150 | °C |
| Maximum Mounting Torque, M6 Mounting Screw | — | 26 | in-lb |
| Maximum Mounting Torque, M6 Terminal Screw | — | 26 | in-lb |
| Module Weight (Typical) | — | 180 | Grams |
| V Isolation (60 Hz, Circuit to Base, All Terminals Shorted, t = 60 sec) | $V_{RMS}$ | 2500 | Volts |

*Figure 29:Diode characteristics*

**Semiconductor device power losses:**

To find the semiconductor losses in Watts at rated operation, we can use Volt-Ampere Method. Adding one Watt-meter at the input and one at the output line to line terminals of the three-phase inverter, by the conservation of complex power we can find approximate total switching loss. Using the datasheet, we added switch and diode parameters to the models.

- Ron is 0.2Ω
- Maximum value of the internal diode of IGBT on voltage is 0.8V
- Maximum on state of diodes is 3.2V
- Slope resistance is so small that we omitted it.

We can say that choosing this Mosfet is an overdesign and Ron is quite high so we expect the power dissipation to be high.

To find the power dissipation on switches we use the topology given in Figure 30 and multiply the resulting power of one switch with 6. Voltage-Current product on one of the switches is given in Figure 31. We took the mean of this plot over one second and found the mean dissipation as 1010 Watts which makes the total dissipation 6060 Watts. We discussed this result with other groups and found out that their Ron value are around 0.01 ohm. So, this problem could easily be fixed with a better Mosfet choice.

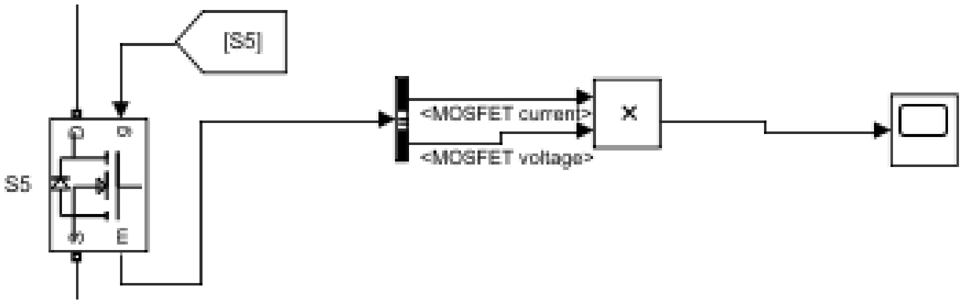



*Figure 30: Topology of the method*

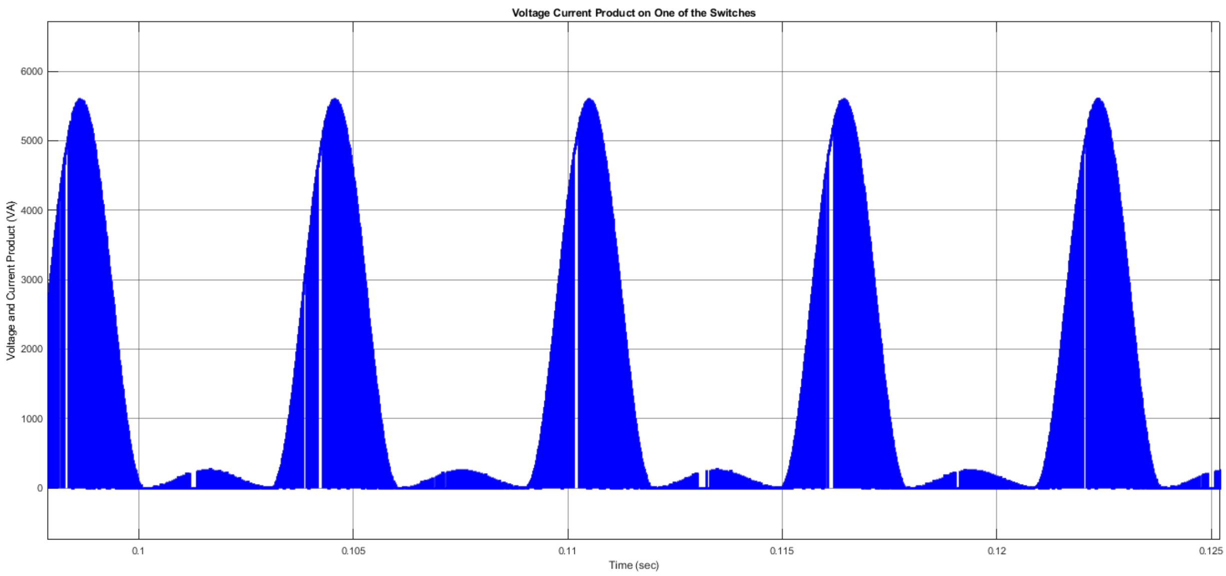



*Figure 31: Instantaneous Power On one of the Switches*

**Efficiency:**

When the load is 60Nm, we observed the steady state electromechanical torque output and the speed. When the speed reaches the steady state value torque output can only reach 220Nm. With these values output power can be found by (10)

$$P_{out} = T * w_m = 220 * 265.9 \approx 58520\,W \quad (10)$$

We used the same method we used in the previous part to find the volt ampere product in the input terminals and found the input by (11)

$$Pin = 3 * 22620 = 67860\,W \quad (11)$$

Overall efficiency is found by (12)

$$\eta = \frac{58520}{67860} = 0.86 = \%86 \quad (12)$$

# 6. CONCLUSION

In this project, we are asked to design of a SM-PMSM Variable Frequency drive using Simulink. Firstly, machine characteristics are examined and applied switching frequency is decided. Then, as the input is 3-Phase AC, a rectifier circuit is implemented with a DC-link filter.

After this point, Sinusoidal PWM method is designed and implemented. The Clarke-Park transformation blocks are designed from scratch. In this part, the drive performance is examined with different cases and for each case, relative plots are obtained.

Then, the very same design is implemented with Space Vector PWM method. In this method readily available blocks are used in design process. Having these two approaches, differences are discussed in detail.

Finally, for real life applications, power semiconductors and other components are chosen according to simulation results, i.e. power ratings, thermal characteristics, operation frequency etc. Then, power analysis and efficiency calculations are performed using the data obtained from datasheets and simulation results. The project is finalized in this step.

All in all, this project helped us to design a motor driver for a SM-PMSM with different PWM modulation techniques as well as real time application considerations all from scratch.

# References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