ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

EE462 — Utilization of Electrical Energy
Project

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

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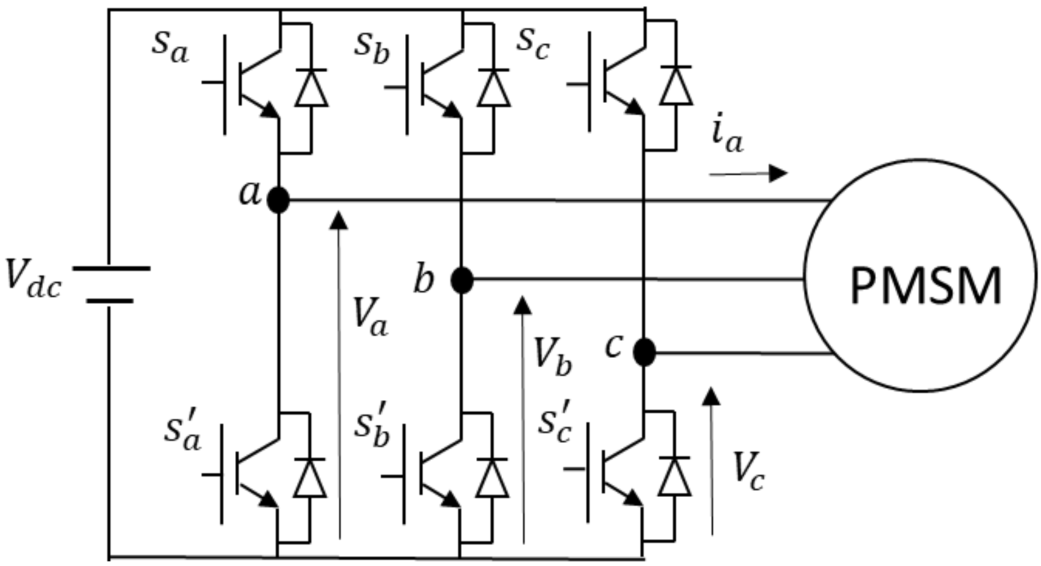

June 2023

1 Part A: Pre-design Stage

1.1 Calculation of Rated Torque

$$T_{rated} = \frac{P_{nominal}}{\omega_{nominal}} = \frac{P_{nominal}}{n_{nominal} \times \frac{2\pi}{60} \times \frac{poles}{2}} = \frac{400 \times 10^3}{1500 \times \frac{2\pi}{60}} \approx 2546.48\ Nm$$

1.2 Calculation of the maximum applied electrical frequency and choosing a suitable switching frequency for the inverter

Since this is a synchronous machine, its rotational frequency (in electrical domain) and the 3phase input supply frequency must be same. In project description, its maximum rotating frequency is given as 2250 RPM, which can be converted into Hz as 37.5 Hz, this is in mechanical domain. In electrical domain since it is a four pole machine its rotational speed is 75 Hz. Therefore maximum applied electrical frequency is 75 Hz

In the given reference paper *"R. Teichmann and S. Bernet, "A comparison of three-level converters versus two-level converters for low-voltage drives, traction, and utility applications," Industry Applications, IEEE Transactions on, vol. 41, no. 3, pp. 855 – 865, 2005"* it mainly compares the efficiency between 2-level and 3-level three phase inverters. The paper states that implementing 3-level inverter with switching frequency above 2 kHz is more suitable and more efficient compared to the 2-level inverter. In this project we are going to implement 2-level three phase inverters therefore it is logical to stay under 2 kHz.

Again in the same paper it says "For moderate harmonic losses in the machine, typically featuring a low leakage inductance, the minimum switching frequency should be substantially above 9-12 times the fundamental frequency".

Our nominal rotational speed is 1500 rpm in mechanical domain so when considering the 4-pole machine it rotates at 50 Hz in electrical domain.

And we learned in the lectures that modulation frequency m_f should be an odd integer, preferably multiple of 3 to reduce harmonics, and 21 is an advised value for it.

By combining the information written above we can select m_f as 21 and resultant switching frequency will be ***1050 Hz***, it will be substantially above 9-12 times the nominal frequency while can still stay under the 2 kHz.

1.3 Designing a DC-link Filter

First of all to find the equivalent resistive load motor at the rated current we should use $\frac{P_{nom}}{(I_{nom(RMS)})^2} = \frac{400000}{(1700/\sqrt{2})^2} = 0.28\Omega$

If we are going to use a Three-phase AC Source: 50 Hz, $400V_{l-l}$

The peak output voltage value will be $400\sqrt{2}$ and average output value will be $V_{DC} = 400V_{l-l}\frac{3\sqrt{2}}{\pi} = 540V$. And frequency of the full bridge rectifier is 6 times of the input frequency therefore 300 Hz.

According to the below equations L and C values can be calculated
$L = \frac{0.013 * V_{DC}}{2pifI_{RMS}} \approx 15\mu H$
To find the cut off frequency f_c
$\frac{\triangle V_o}{\triangle V_r} = (\frac{f_c}{f_r})^2$
Where $\triangle V_o$ is desired ripple voltage, $\triangle V_r$ is ripple without filtered voltage and f_r is the ripple frequency which is 300 Hz in three phase full bridge diode rectifier as stated above.

In three phase full bridge diode rectifier with $400V_{l-l}\triangle V_r = 75.8V$

Lets assume we will be fine with %3 percent voltage ripple. Dc voltage is 540 V

$V_{ripple} = (3/100) * V_dc = 16.2V$

So by inserting the known values f_c can be found as 138 Hz

Then capacitor value can be calculated with

$\frac{1}{4(\pi)^2(f_c)^2L} = 80mF$ 80 mF is a quite bulky capacitor lets increase the inductance to 1 mH and calculate again $\approx = 1.3mF$ so lets use 1 mF and 1 mH capacitor and inductor respectively. The corresponding output voltage plot of the DC-link filter is given below. There is 8 V ripple, which corresponds to %1.5 ripple.

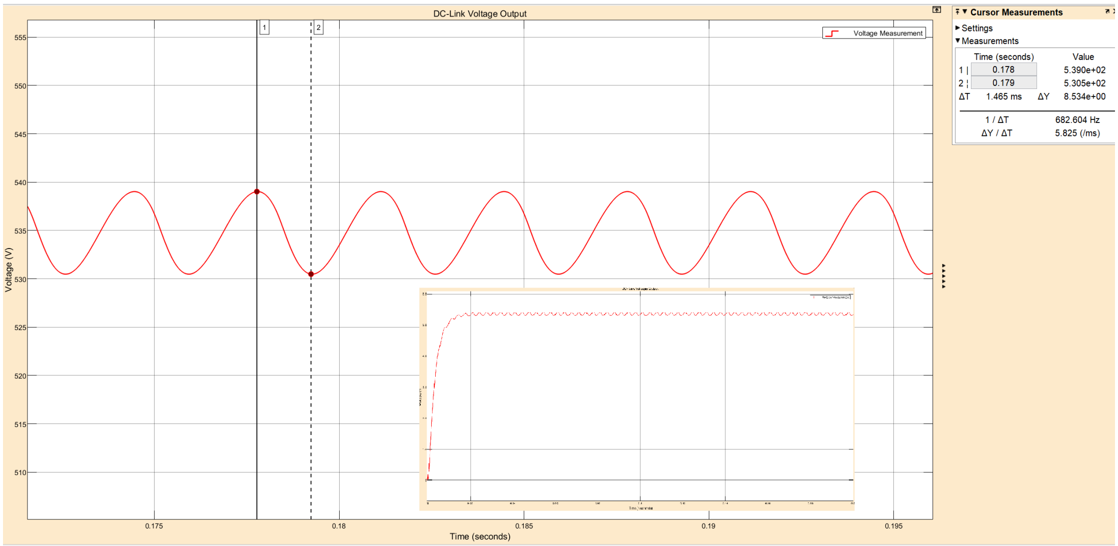

Figure 1: Output Voltage of the DC-link Filter

After implementing the circuit with 1 mF capacitor and 1mH inductor it is observed that L and C resonate and produce high voltages, then it is also observed that inductor does not provide much advantage so we decided to use 10 mF parallel capacitor only.

2 Part B: Sinusoidal PWM

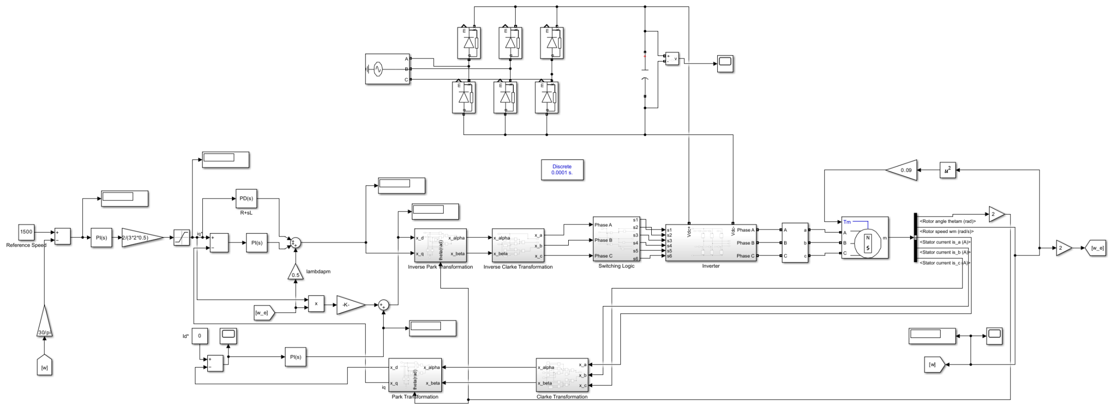

Figure 2: Sine PWM Full Circuit Block

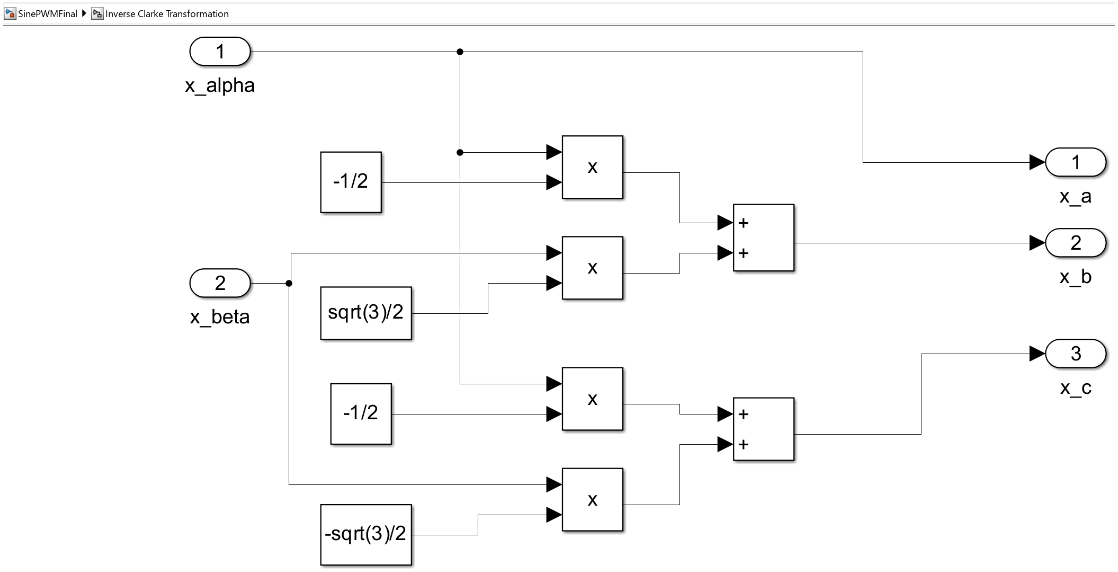

Figure 3: Inside of the Inverse Clarke Transformation Block

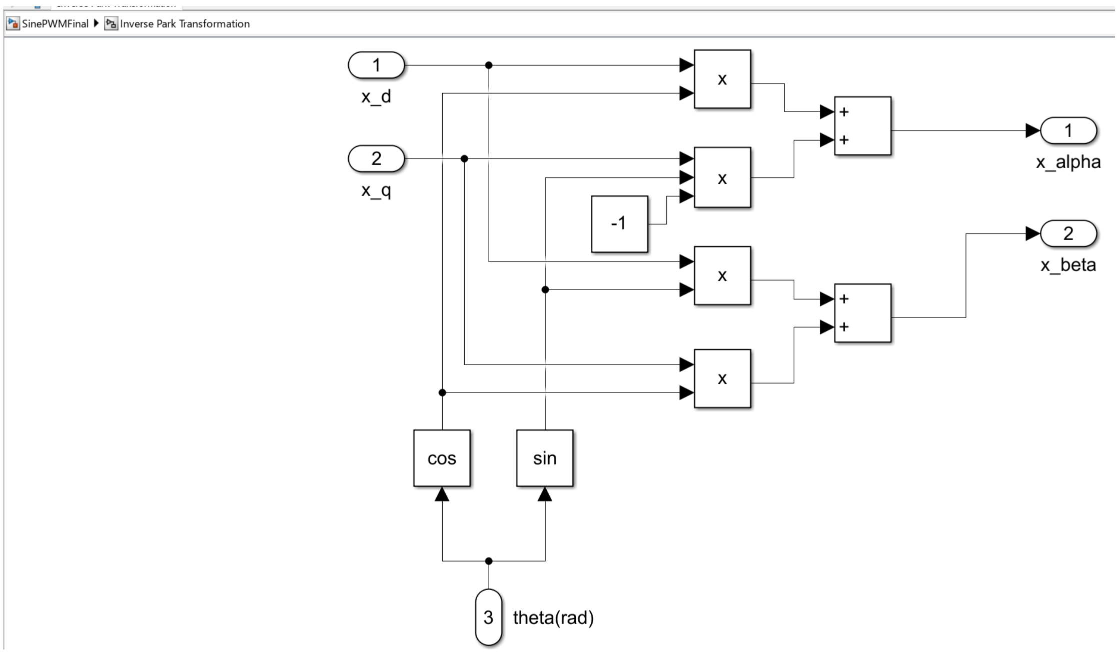

Figure 4: Inside of the Inverse Park Transformation Block

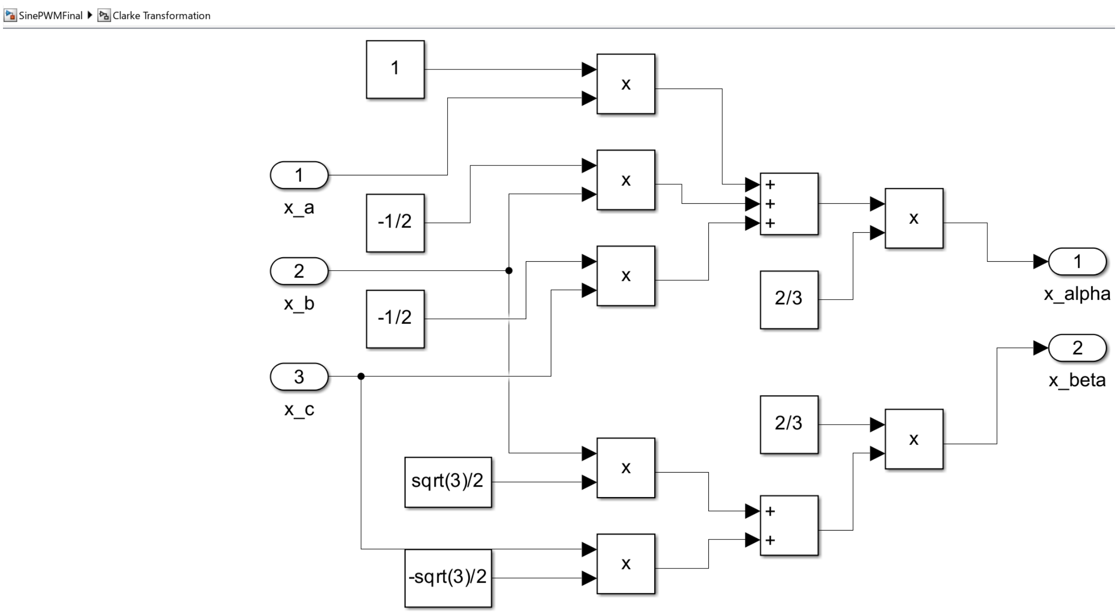

Figure 5: Inside of the Clark Transformation Block

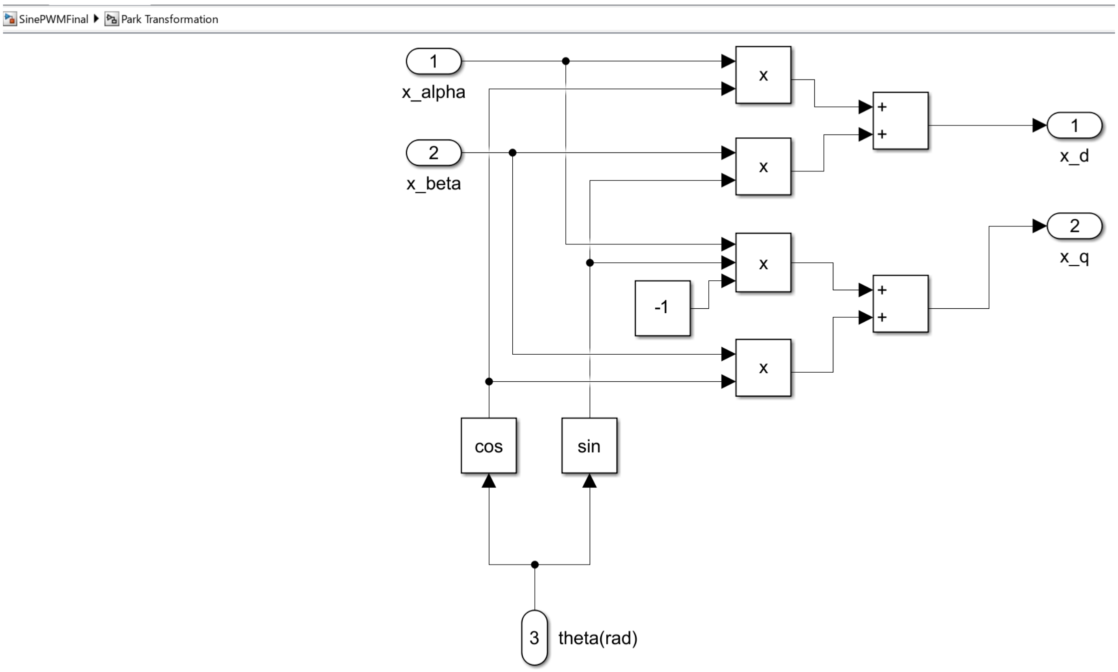

Figure 6: Inside of the Park Transformation Block

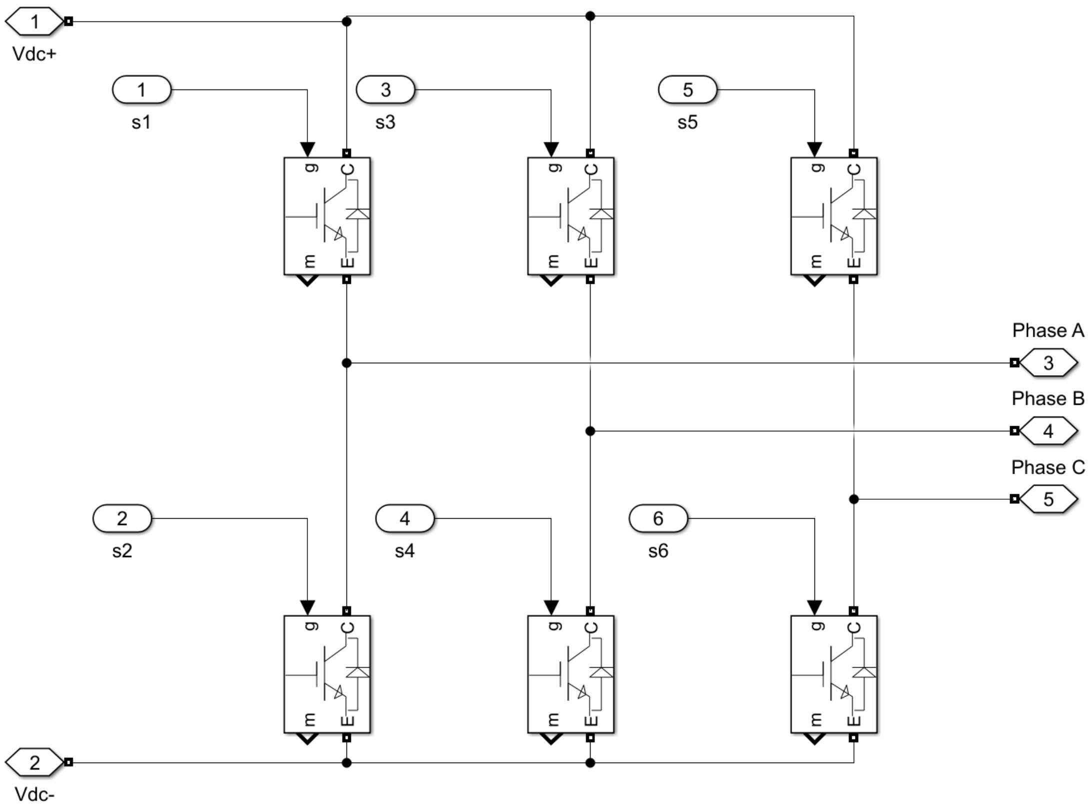

Figure 7: Inside of the Inverter Block

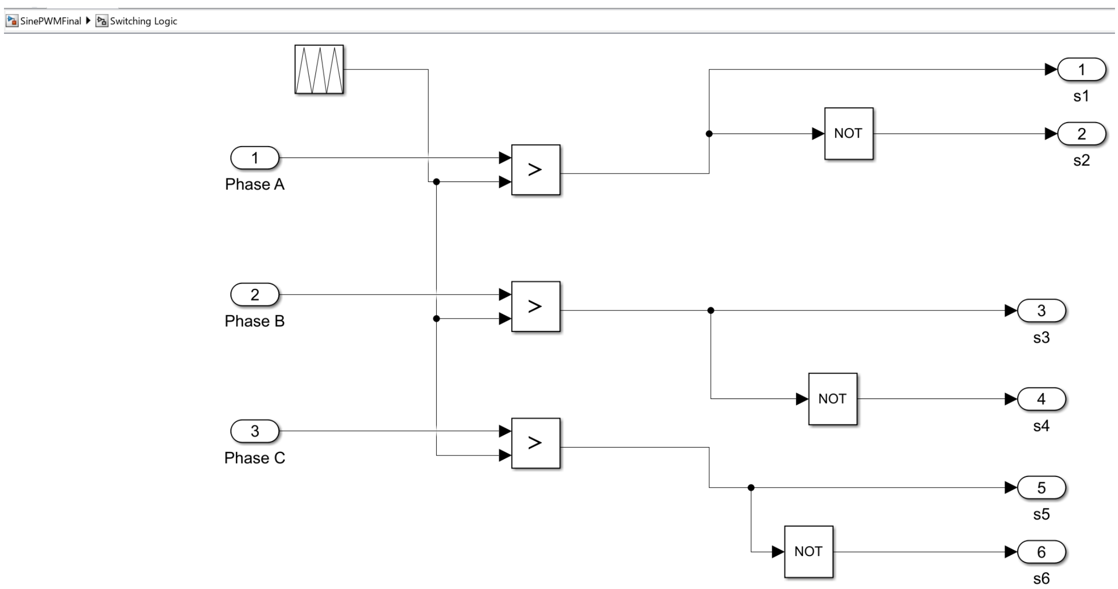

Figure 8: Inside of the Switching Logic Block

2.1 Fan load transition of %90 of the rated speed case analyze and plot

To calculate the equivalent Inertia

$1/2 * J_{load} * (\omega_{load})^2 + 1/2 * J_{motor} * (\omega_{motor})^2 = 1/2 * J_{eq} * (\omega_{motor})$ where $\omega_{motor} = \omega_{load}$ since direct drive.

So $J_{eq} = 241\ kgm^2$

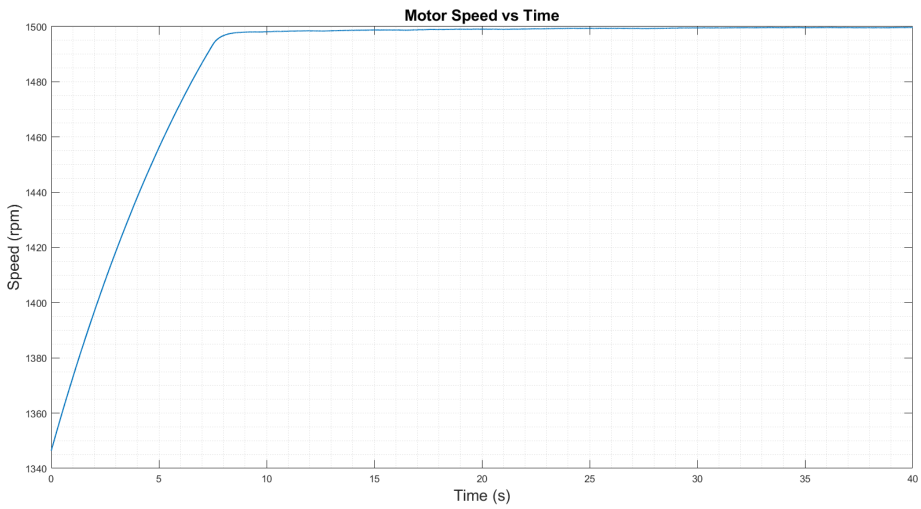

Figure 9: Motor Speed vs Time Plot when motor is accelerating

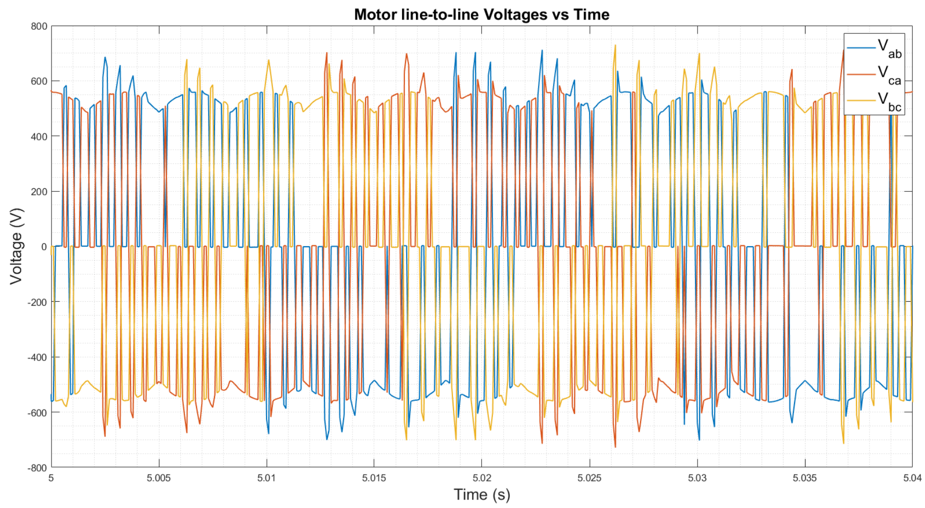

Figure 10: Motor line-to-line Voltages vs Time Plot when motor is accelerating

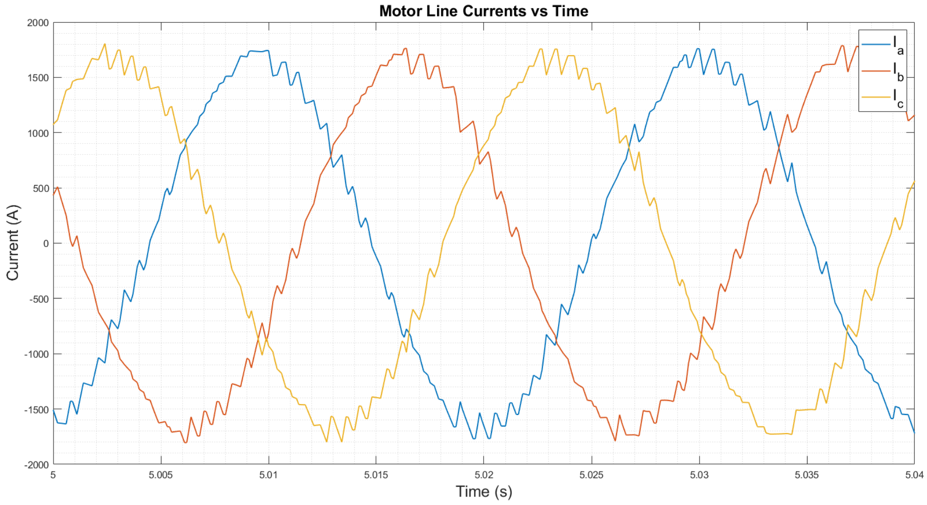

Figure 11: Motor Line Currents vs Time Plot when motor is accelerating

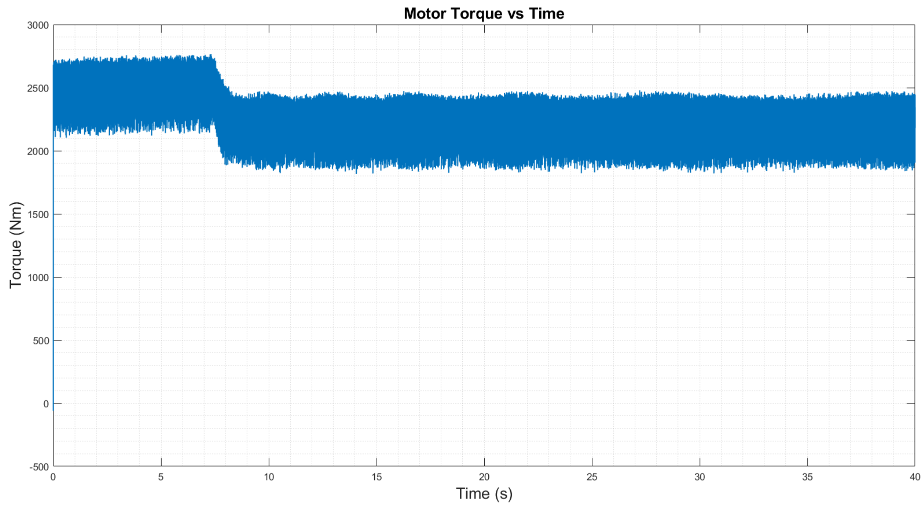

Figure 12: Motor Torque vs Time Plot when motor is accelerating

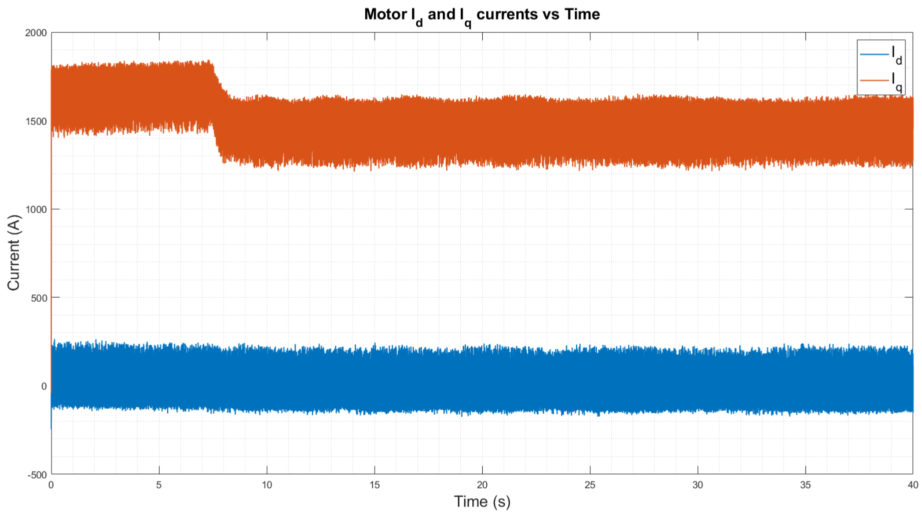

Figure 13: Motor dq-axis Currents vs Time Plot when motor is accelerating

The transition time of the system from 90% rated speed to rated speed is around 8 seconds with 0.2% error. The system further corrects this error at around t = 40s.

2.2 While the motor is running at rated speed with the fan load then load is removed and the speed reference is kept constant case

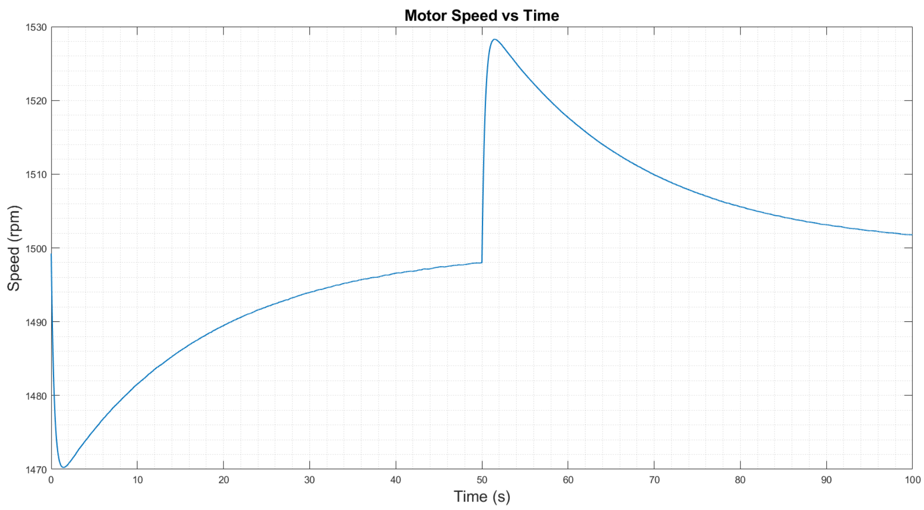

Figure 14: Motor Speed vs Time Plot with load disconnected at t = 50s

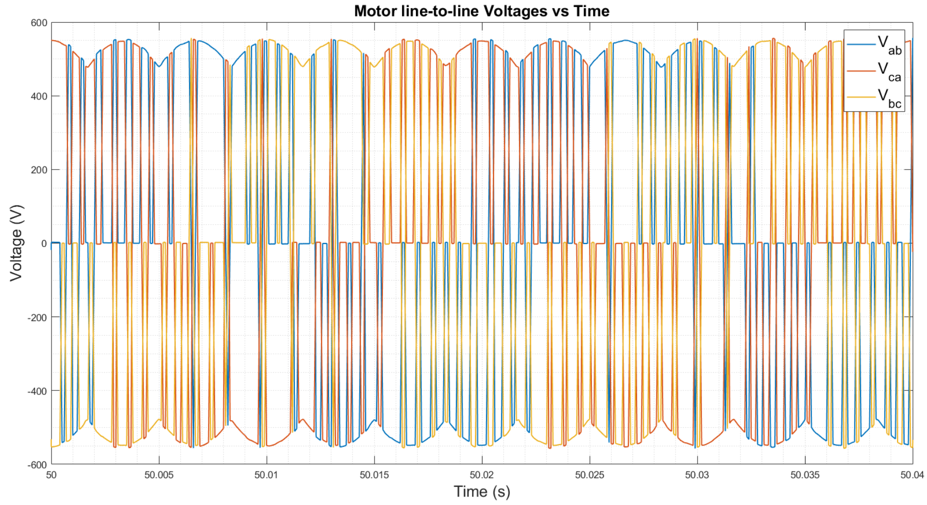

Figure 15: Motor line-to-line Voltages vs Time Plot with load disconnected at t = 50s

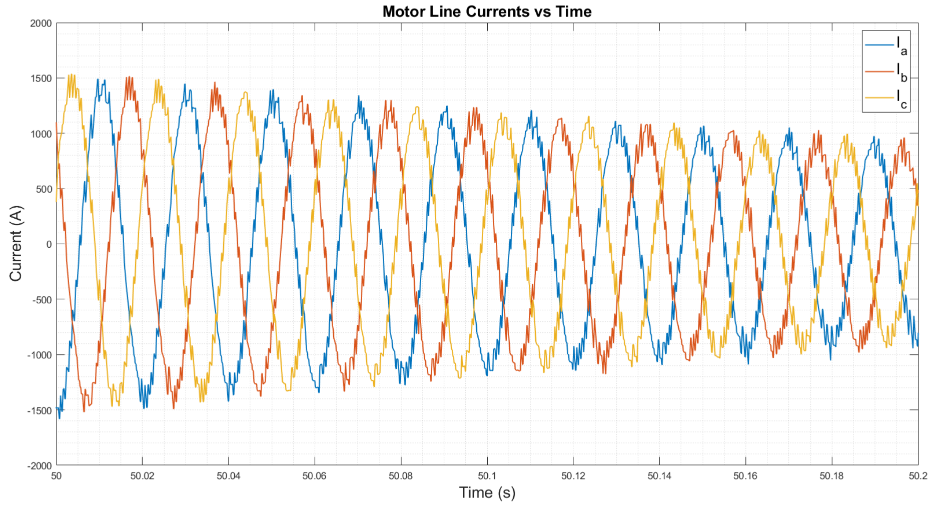

Figure 16: Motor Line Currents vs Time Plot with load disconnected at t = 50s

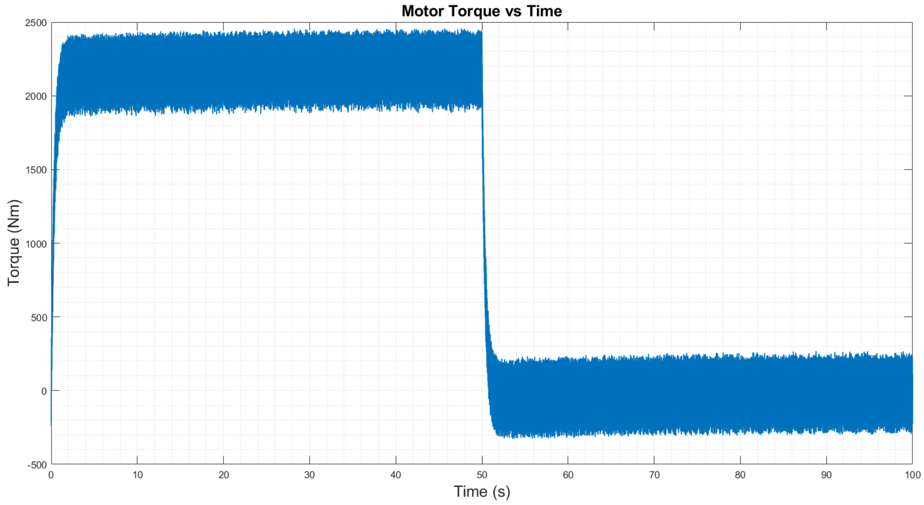

Figure 17: Motor Torque vs Time Plot with load disconnected at t = 50s

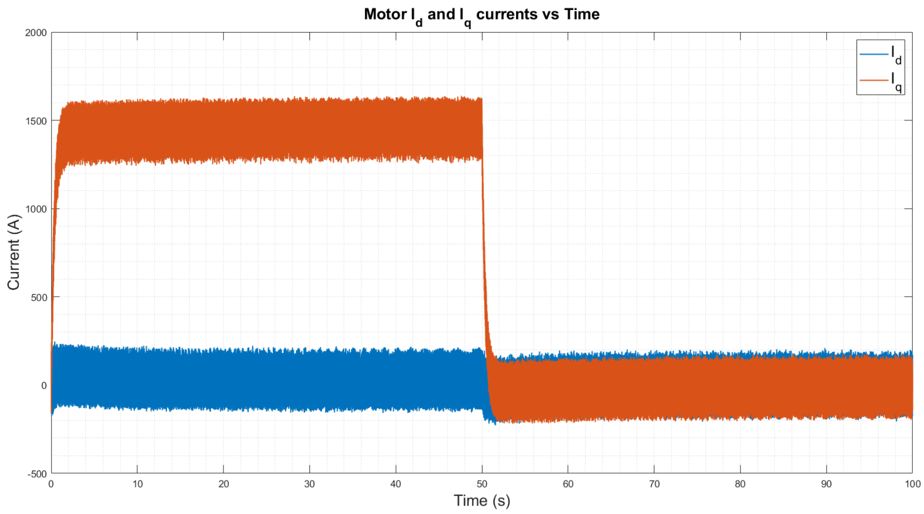

Figure 18: Motor dq-axis Currents vs Time Plot with load disconnected at t = 50s

2.3 While the motor is running at rated speed at no-load, the speed reference is reversed

Braking Resistor Design

As we are not much experienced with braking resistor design, we designed it iteratively. We connected a small resistor of 1 Ω in series with an IGBT initially. We couldn't achieve the desired 600V limiting effect so we decreased the resistance value until a satisfactory design was achieved. The final resistance value turned out to be 0.36 Ω.

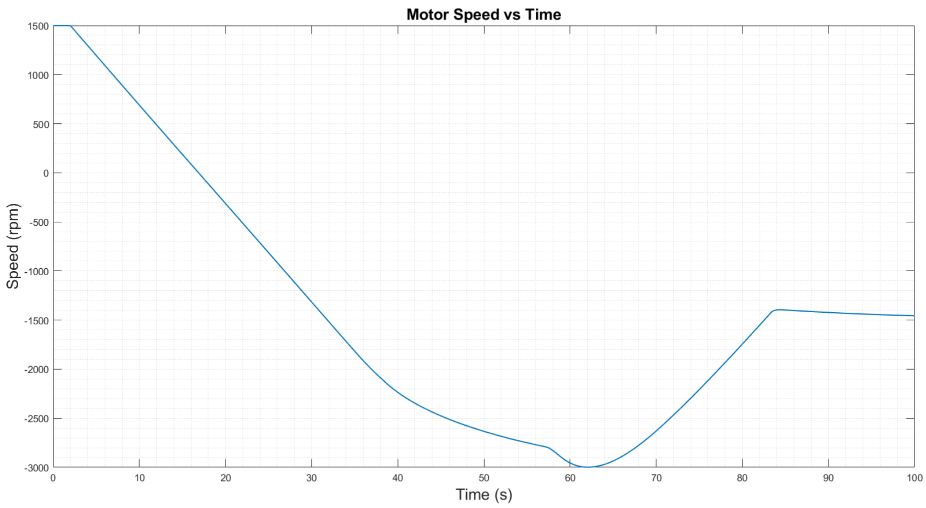

Figure 19: Motor Speed vs Time Plot with speed reference reversed at t = 2s

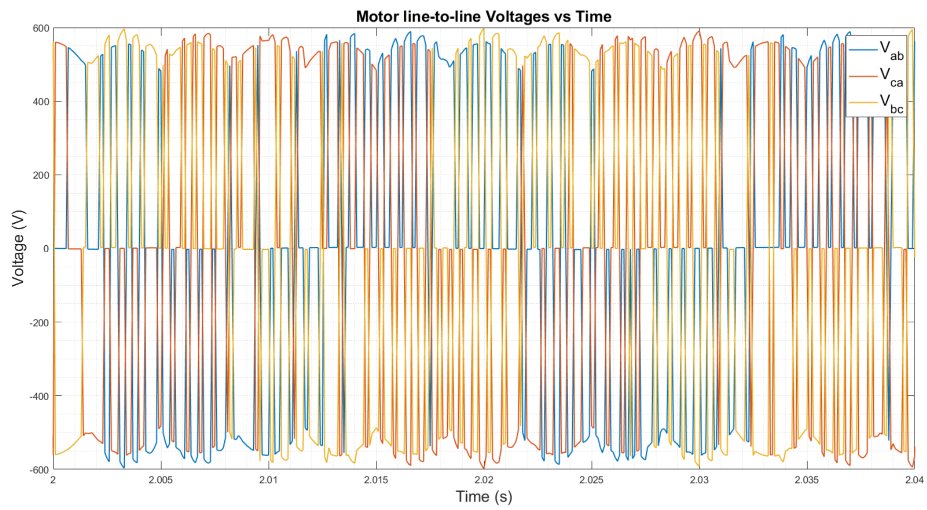

Figure 20: Motor line-to-line Voltages vs Time Plot with speed reference reversed at t = 2s

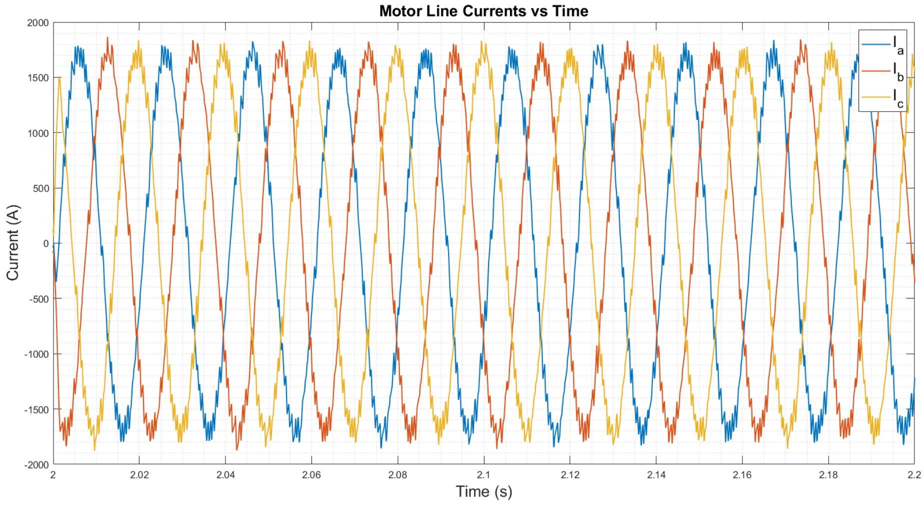

Figure 21: Motor Line Currents vs Time Plot with speed reference reversed at t = 2s

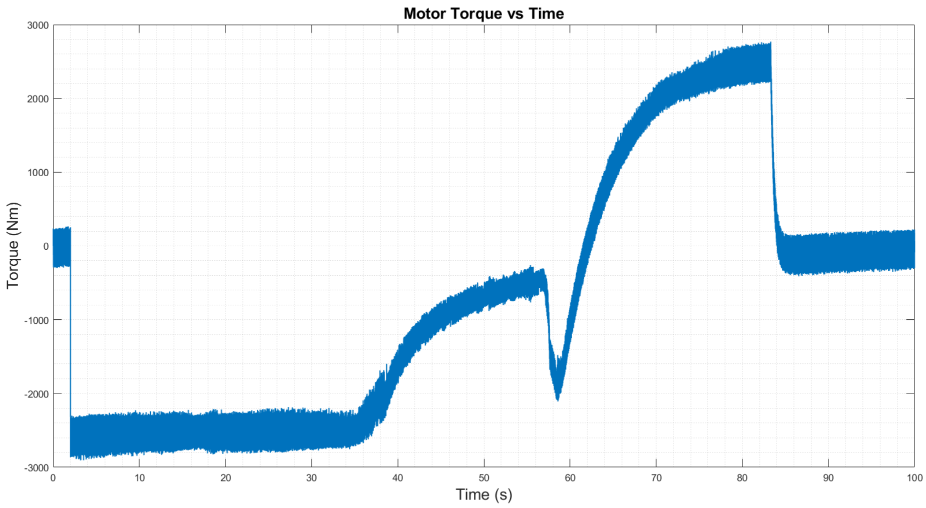

Figure 22: Motor Torque vs Time Plot with speed reference reversed at t = 2s

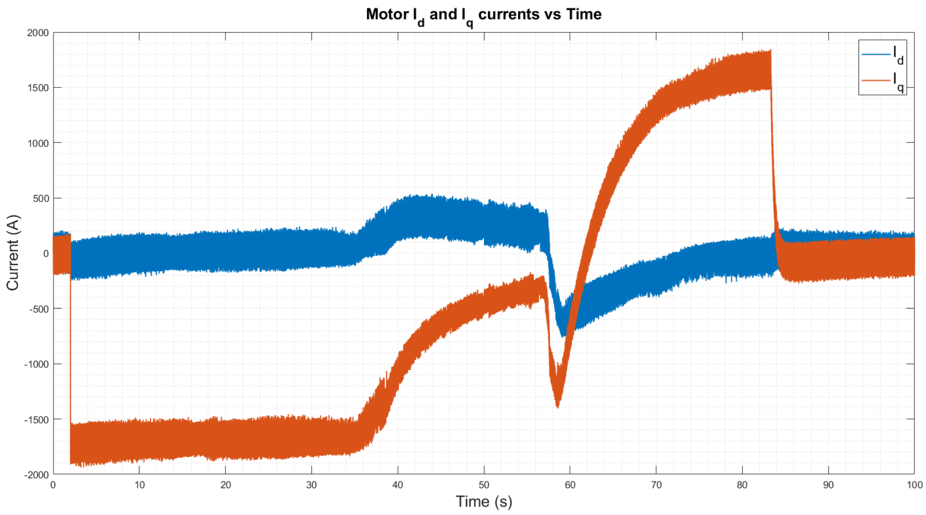

Figure 23: Motor dq-axis Currents vs Time Plot with speed reference reversed at t = 2s

2.4 While the motor is running at rated speed at half of the rated torque and inertia of the load = 240 method to run the motor at %150 of the rated speed

Rated speed = 1500 RPM = 157.1 rad/sec, half of the rated torque 2546.48/2 = 1273.28, %150 rated speed 2250 RPM = 235.6 rad/sec.

In this case we should apply field weakening to the motor by applying $-i_d$ current

Remember we have $I_{limit} = 1700 = \sqrt{i_d^2 \times i_q^2}$ And remember the torque equation $T_{em} = \frac{3 \times pp \times \lambda_{pm} * i_q}{2}$ so by inserting the values $1273.28 = \frac{3 \times 2 \times 0.5 \times i_q}{2}$

From above calculation i_q found as 848.85 then from the current limit relation i_d found as -1473 A.

But when -1473 A is directly applied as a reference id the total current limit is broken and it exceeds 1700 A. So it is better to apply the current limit equation to the id reference as seen below. In this configuration we let the controlled decide on id and iq.

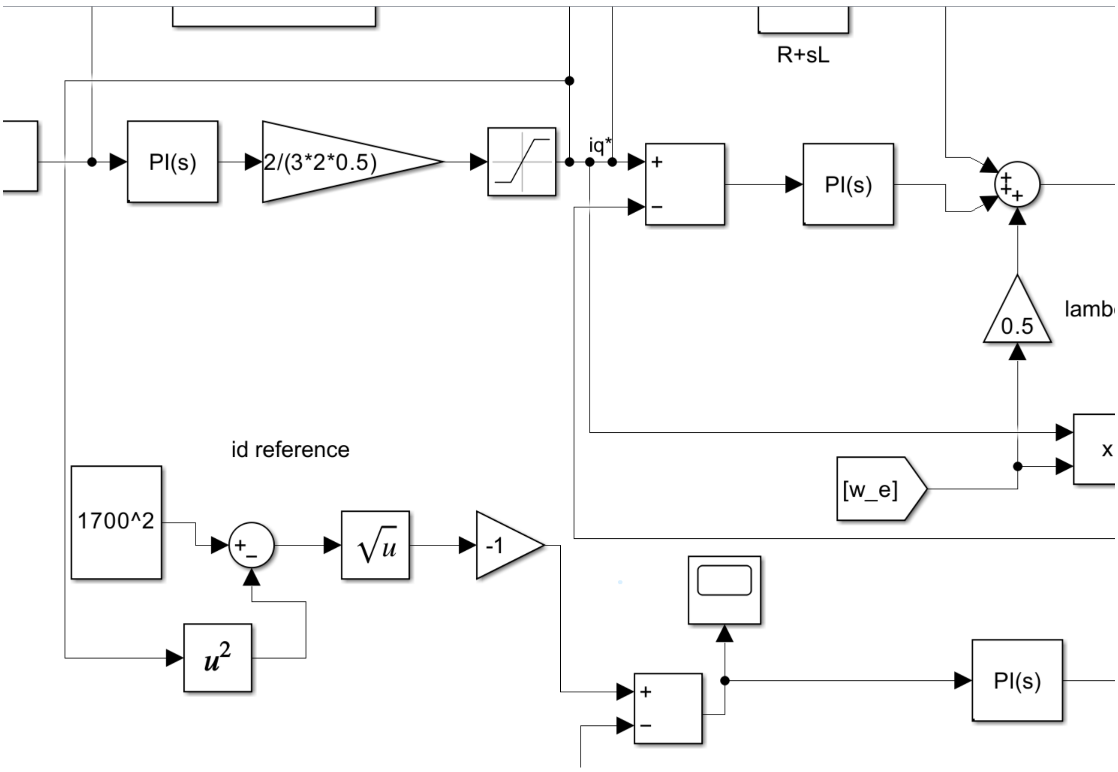

Figure 24: Id current reference tracking

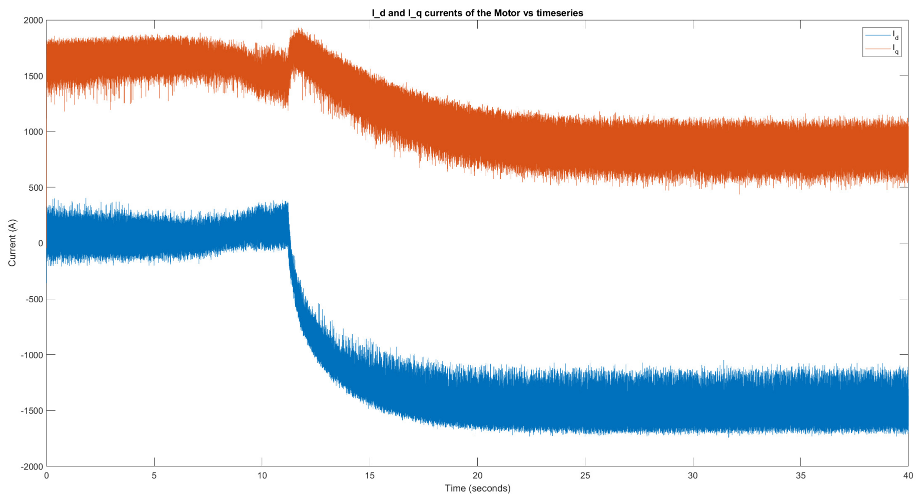

Figure 25: Id and Iq current of Motor vs Time Plot

From the above plot it can be seen that id current is around -1473 which is the previously calculated value.

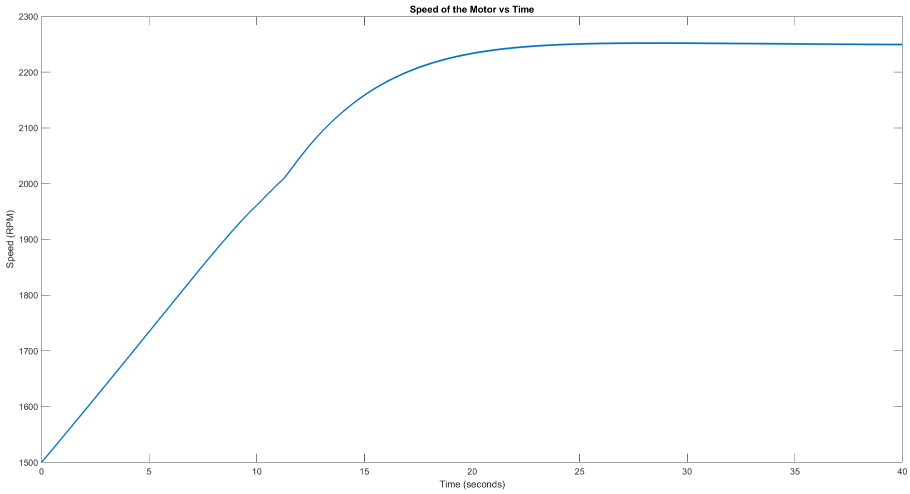

Figure 26: Speed of the Motor vs Time Plot

3 Part C: Space Vector PWM (SV-PWM)

3.1 Repetition of Part B

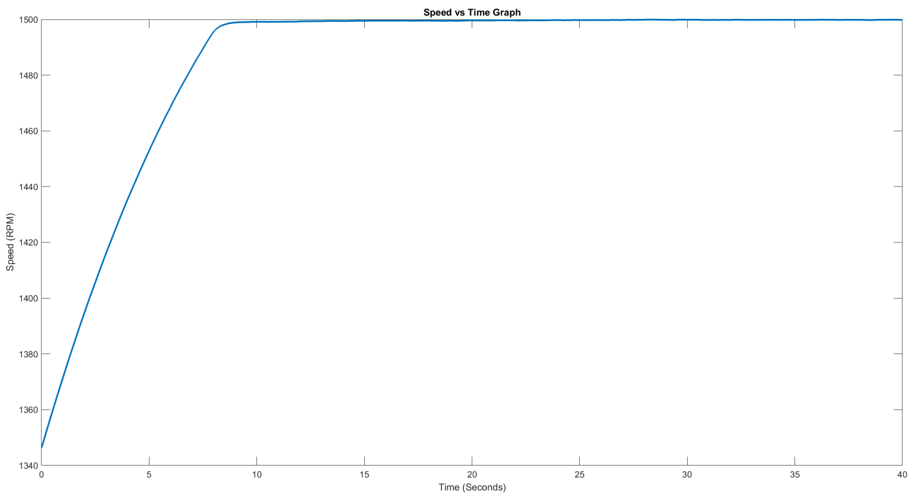

Figure 27: Speed of the Motor vs Time Plot

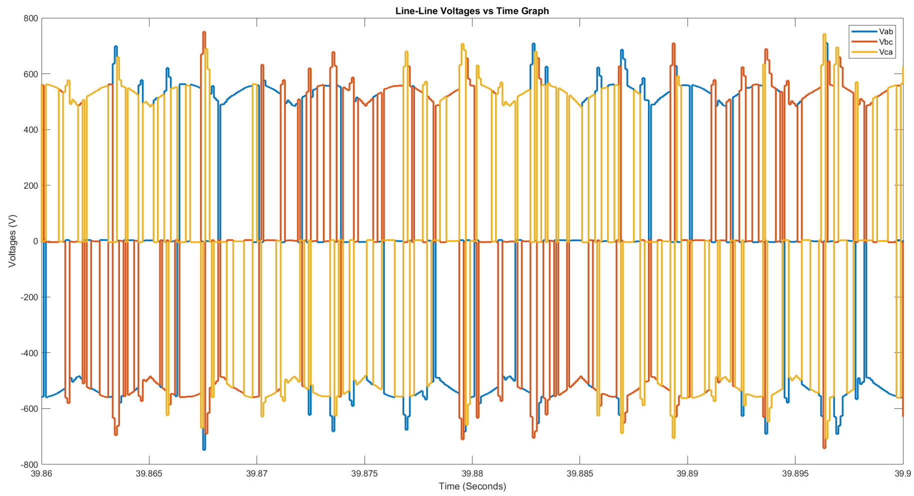

Figure 28: Line to Line Voltages vs Time Plot

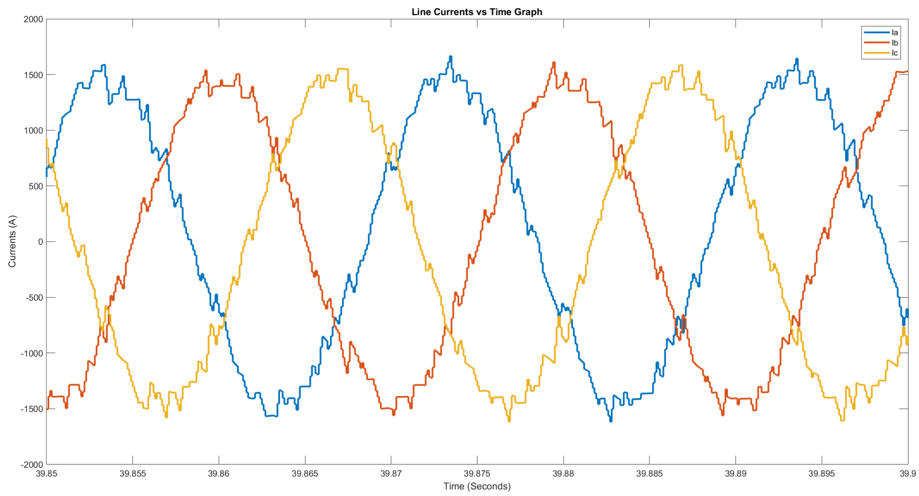

Figure 29: Line Currents vs Time Plot

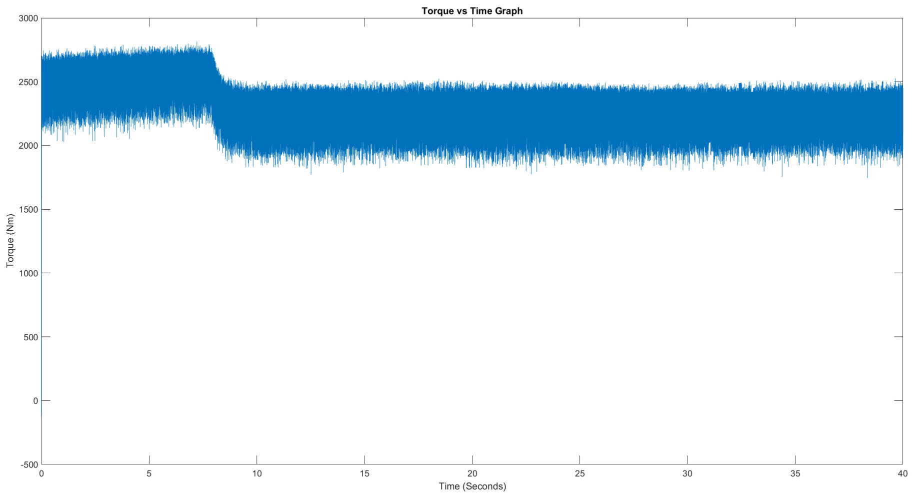

Figure 30: Torque vs Time Plot

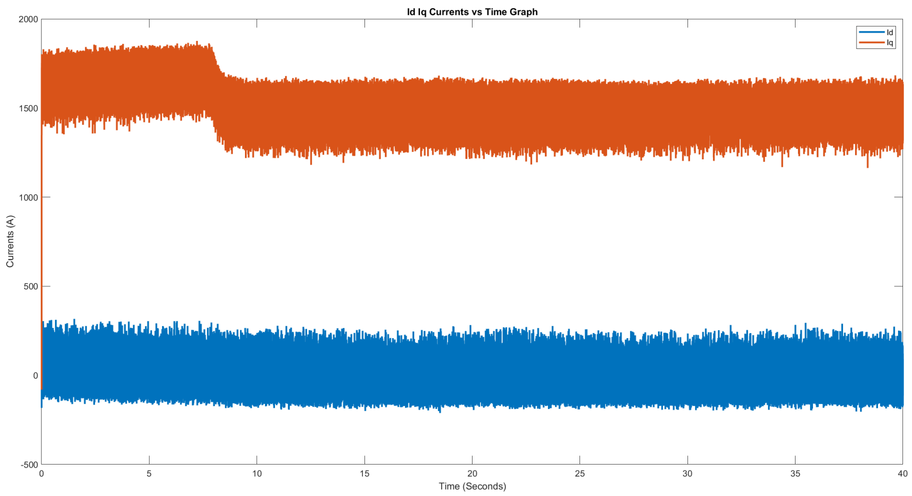

Figure 31: Id Iq vs Time Plot

Transition time is 9 seconds to reach the rated speed of 1500 RPM (157.1 rad/sec)

3.2 3-phase Reference Voltage Wave-forms for the Sine-PWM and SV-PWM for rated operation.

For the rated operation it is assumed that load is still there (therefore J=241) and initial speed is at rated speed (157.1 rad/sec).

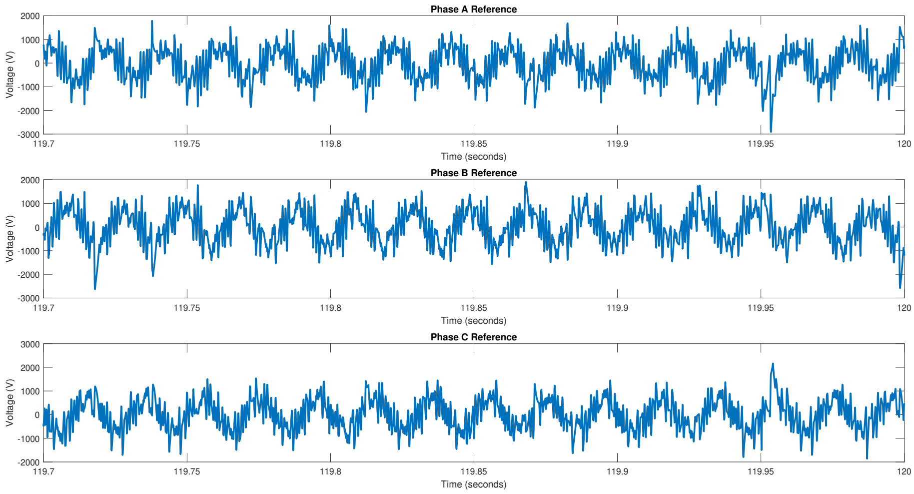

Figure 32: Phase Reference Voltages at Steady State for Sine PWM

To have the three phase waveform of SV-PWM the inverse Clarke Transform we implemented is used.

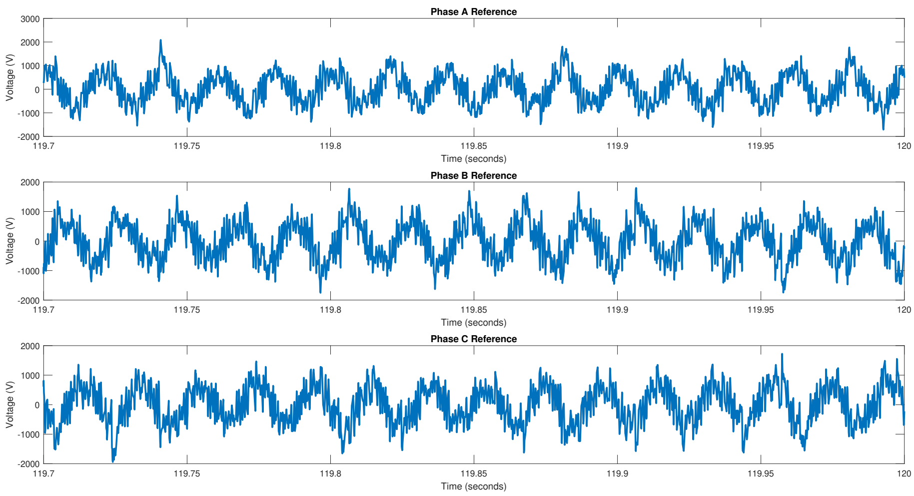

Figure 33: Phase Reference Voltages at Steady State for Space Vector PWM

3.3 Comparing the FFT components of the Line Currents for Sine-PWM and SV-PWM.

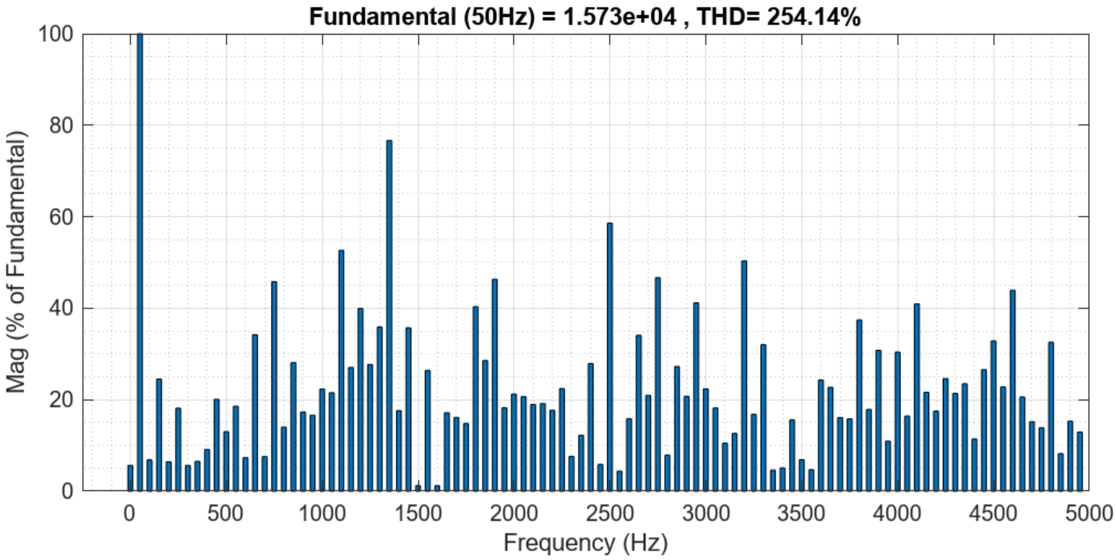

Figure 34: FFT Analysis of The Sine-PWM

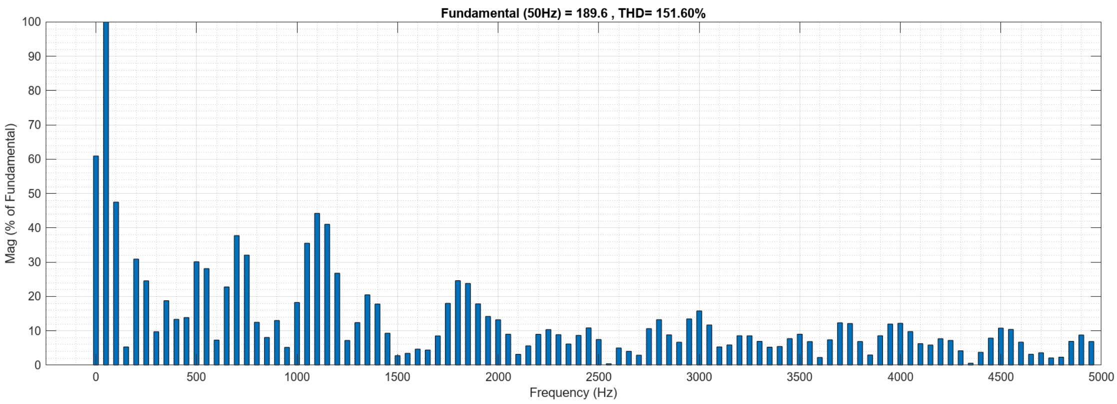

Figure 35: FFT Analysis of The SV-PWM

According to the results obtained from simulation, there is a dramatic decrease in THD values of line currents.

3.4 Main Differences Between Sine-PWM and SV-PWM.

The main difference of these techniques is the implementation manner. SV-PWM utilizes more dynamic control algorithm to obtain desired output. Moreover, as it can be seen from the previous part, SV-PWM provides output with less harmonics, approaching to pure sinusoidal. On the other hand, SPWM requires less complex algorithm to control. In overall, SV-PWM is a better solution for a high performance drive application despite its complexity.

4 Part D: Component Selection

4.1 Commercial Product for Switch

1.7kV 4.8kA IGBT Module

Selection of IGBT has several considerations. Two of them are voltage and current ratings. According to the simulations, single IGBT should be capable of conducting 1.8 kA and bearing 750V. Another important parameter is switching losses. The desired IGBT would have very low switching losses. Another important parameter is conduction loss on collector emitter junction. Similar to switching, the less the junction resistance, the less conduction loss would be. The final consideration is price. The cheaper solution on switching component is desirable.

4.2 Calculation of Losses on Selected Switch

Motor will operate at 1500 rpm at rated, which corresponds to 50 Hz operation of single phase due to existence of 4 poles. According to datasheet, single IGBT will have 450 mJ turn on and 870 mJ turn off energy loss in a period. The frequency modulation is 21, which means there will be 21 switching in an electrical period and 1050 switching in a second. 1.386 kJ switching loss will occur in a single IGBT. Another source of loss is conduction. According to datasheet, IGBT has 2.3V $V_{ce,sat}$ when it is conducting 2.4 kA, allowing collector to emitter resistance to be around $0.96m\Omega$. According to the simulation, IGBT has 806 Arms. Then, conduction loss is calculated as 622.56 J. As a result, there will be approximately 2kW energy loss on a single IGBT, making 12 kW energy loss in total. 2 kW power dissipation per IGBT leads the module to have 120 K temperature rise as there are 3 IGBT in a module. (Assumed there is a heatsink with thermal resistance 3K/kW and ambient temperature is 298K.) Therefore, utilization of 2 of the IGBT's in a module will be safe, leading maximum temperature of the module to be around 280K.

4.3 Selection of IGBT Driver

1.7kV 20A IGBT Gate Driver

The driver meets the required operating conditions. It drives IGBT's with $V_{ce,max}$=1.7kV. Moreover, it has 20A gate current capability at 15V gate voltage, which allows gate to be charged within turn-on time specified in the datasheet of the IGBT. Moreover, it supports frequency up to 15kHz, which is sufficient for the operation described. Therefore, this IGBT driver is a good solution for the problem.