APRIL 25, 2017

DESIGN OF DC MOTOR DRIVER

SECOND PROJECT REPORT

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INTRODUCTION

This is a simulation based project in which DC Motor driver application is done. In order to reach this achievement, a DC Motor will be driven by a rectified and filtered input voltage and using a chopper circuit. Therefore, PWM blocks will be implemented to use this chopper in four-quadrant. Also, in this project the concept of dynamic braking will be investigated. Moreover, controller types for DC Motor application will be investigated and they will be compared. At the end, devices will be suggested for this DC Motor driving application.

PART A – PRELIMINARY DESIGN

In this project three phase sinusoidal input voltages are rectified with diode rectifier circuit and it is filtered with an L-C filter to obtain DC voltage at the end. The rectifier diagram can be seen in below.

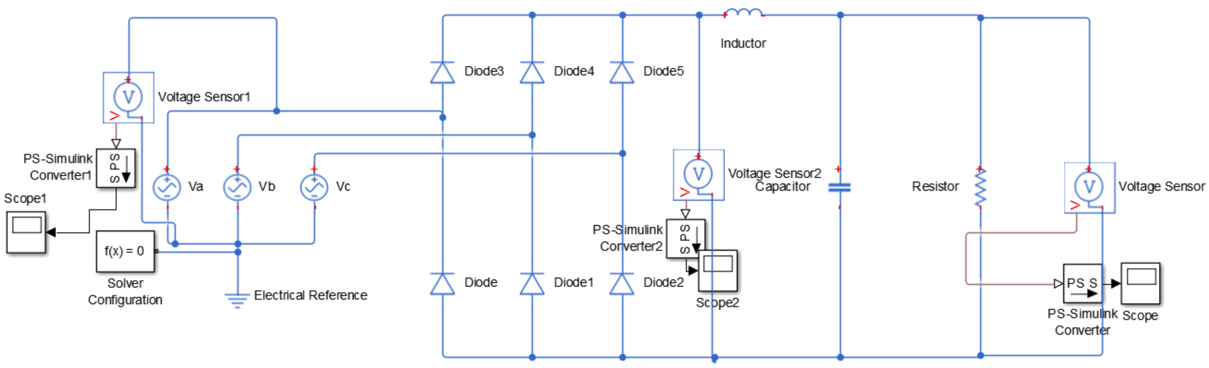

Figure 1: The rectifier circuit

In a three phase full bridge rectifier the output voltage oscillates with the $3*f_s$ frequency which is equal to 150Hz in our case. Therefore, this fundamental harmonic should be eliminated to get a nearly pure DC voltage. Therefore, the L-C low pass filter should be designed such that the ω_c is far enough to 150Hz. Thus, designing the L-C filter the inductance value is chosen as 40mH and the capacitor is chosen as 1mF.

$$f_c = \frac{1}{2 * \pi * \sqrt{LC}} = 25.17\ Hz$$

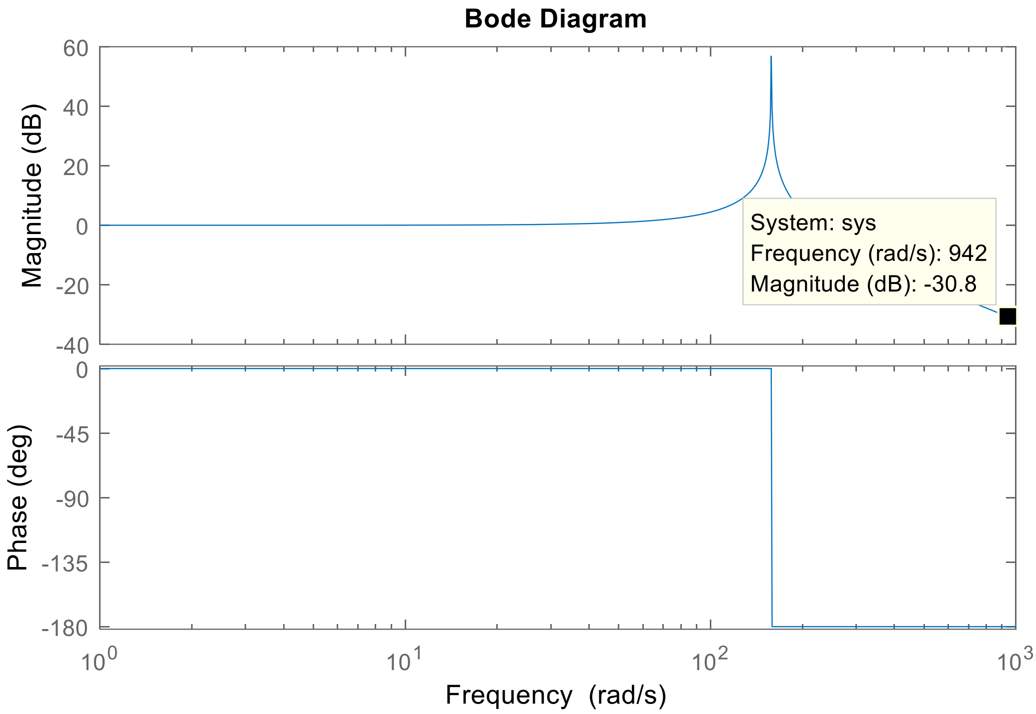

Figure 2: Bode plot of the LC filter

As seen on bode plot, this filter stops the 150Hz/942rad/s harmonic.

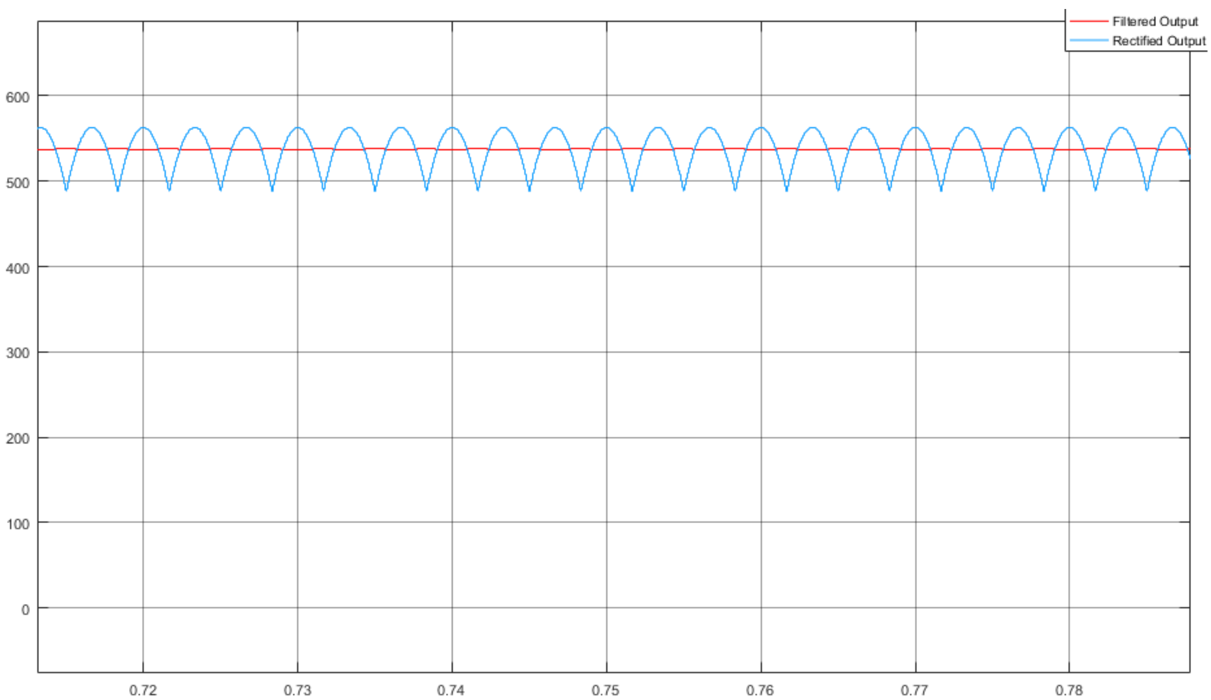

Figure 3: Rectified output voltage and filtered output voltage graph

Secondly, in order get ripple less than 1% on the armature current, the switching period should be selected much less than the electrical time constant of the DC motor.

$$\tau = \frac{La}{Ra} = 8.7ms$$

$$T \ll \tau \rightarrow T \leq \frac{\tau}{10} = 0.87ms$$

$$f \geq 1.15\ kHz$$

Since in this project unipolar PWM generator is used, the carrier signal should be larger than half of this frequency. Considering a safe operation, frequency of the carrier signal is chosen as 15 kHz.

PART B – MODELLING AND SIMULATION

Voltage Ripple

The rectifier circuit with a resistive load which is used instead of DC motor is given below.

$$R = \frac{V_{rated}}{I_{rated}} = \frac{360V}{12.78A} = 28.17\Omega$$

For this resistance value, the voltage waveforms are the following ones.

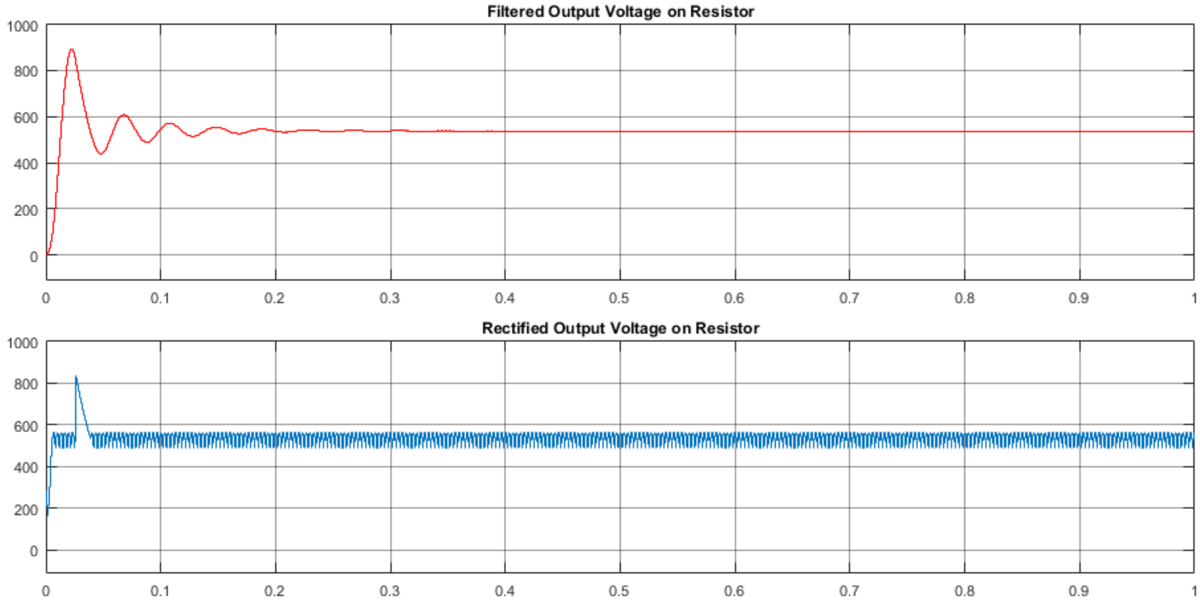

Figure 4: Rectified and Filtered Output Voltage without Zoom

The zoomed output voltage graphs are given in Figure 3.

Motor-Drive Modelling

In this project the four quadrant chopper circuit is modelled using MOSFETs. The body diodes of the MOSFETs enable to operate in all quadrants. This chopper is driven by a unipolar PWM generator sub-block which is also modelled during this project. Unipolar PWM block is capable of driving switches for four quadrant application. The current can conduct in both directions and since the unipolar PWM block can decrease armature voltage up to zero, the speed can be either direction. Therefore, this system can operate in four quadrant applications.

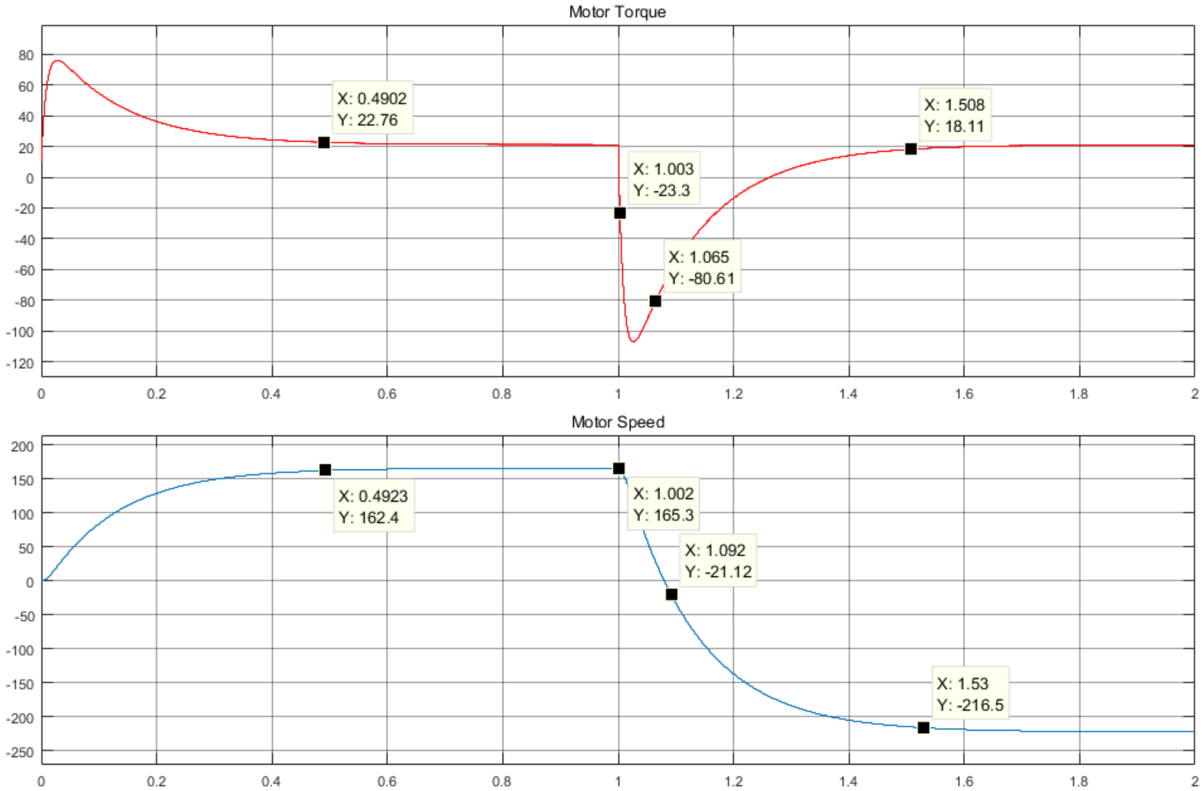

Figure 5: Motor Speed and Motor Torque graphs which show four quadrant characteristics

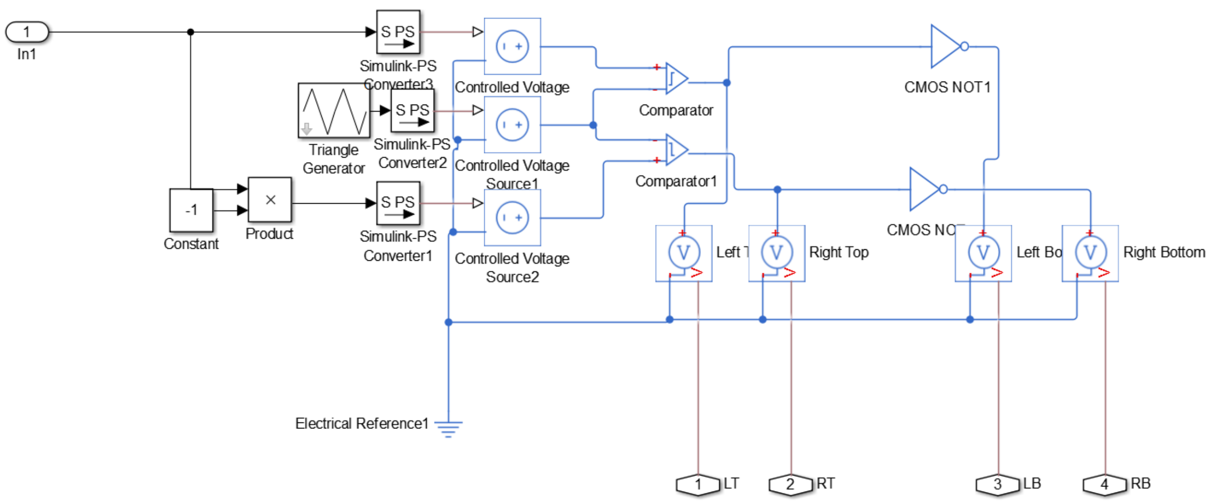

Figure 6: Unipolar PWM Generator Sub block

This sub-block includes an input which is the reference level and an advantage is that, this input value is directly equal to the effective duty cycle applied to the armature. Therefore, controlling the duty cycle will be easy. The whole system with DC input can be seen in the following figure.

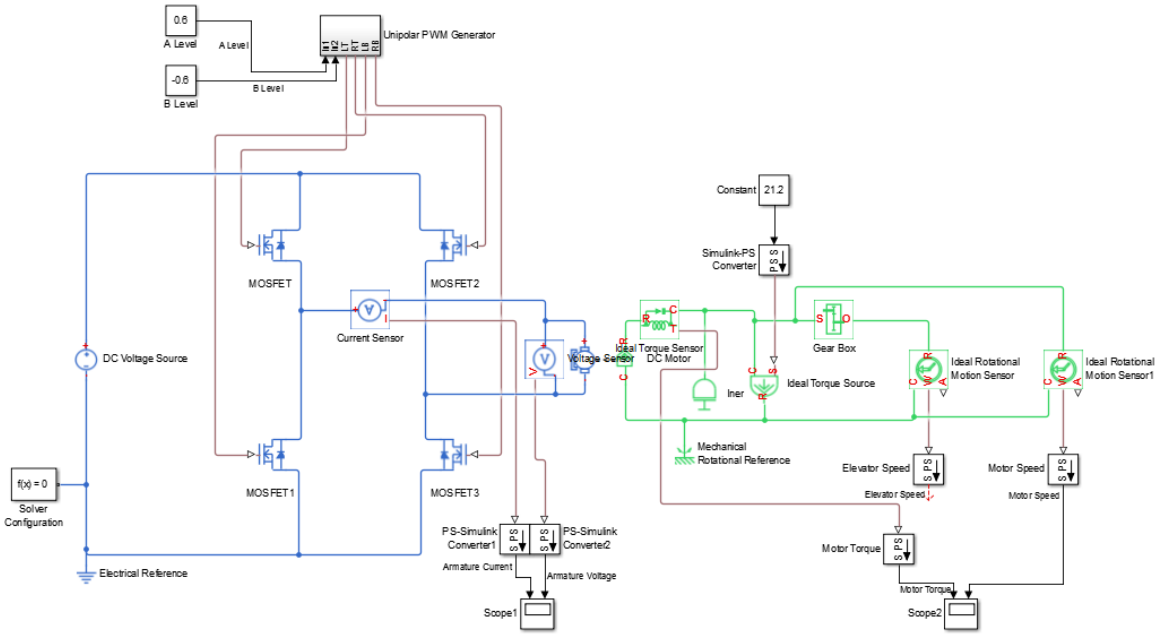

Figure 7: Chopper Circuit with DC Voltage Source

$$V_{dc} = 1.35 * \sqrt{3} * V_{l-n} = 537.8V$$

With this circuit, the DC motor is driven with 60% duty cycle and the obtained waveforms are the following ones.

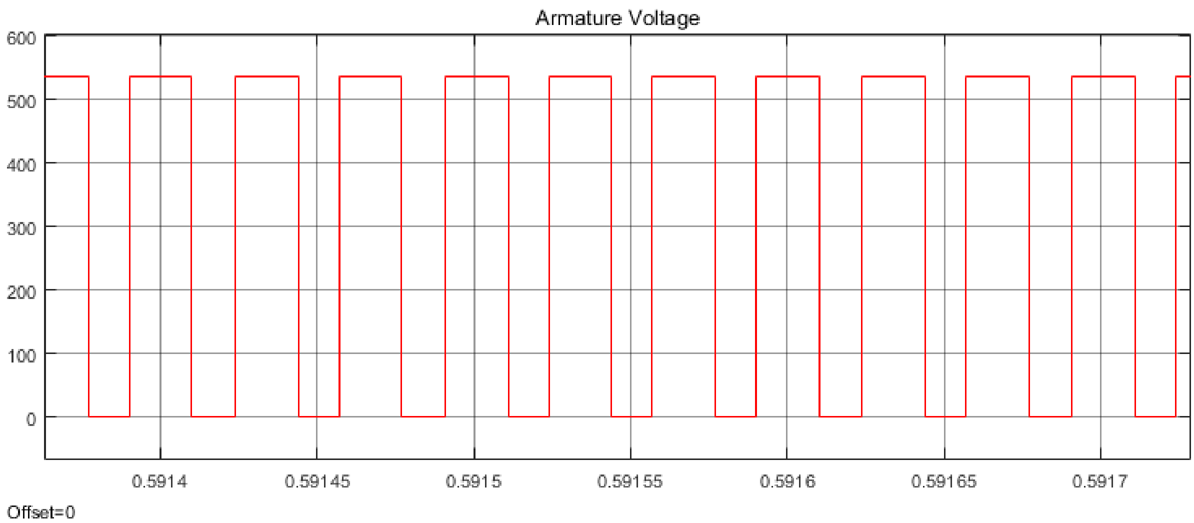

Figure 8: Armature Voltage Graph for 0.6 Duty Cycle

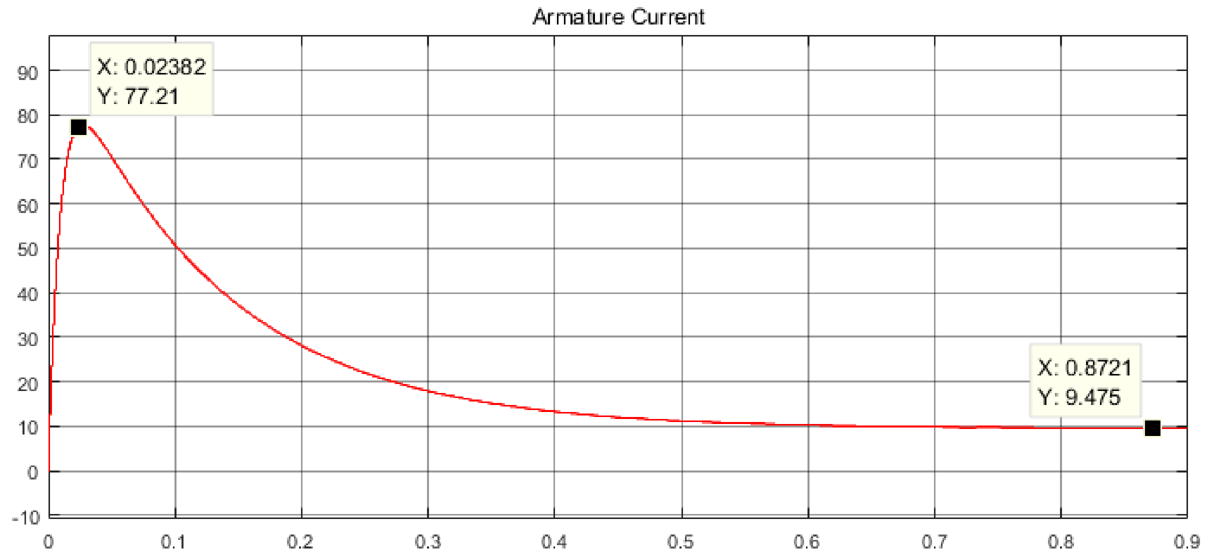

Figure 9: Armature Current without Zoom

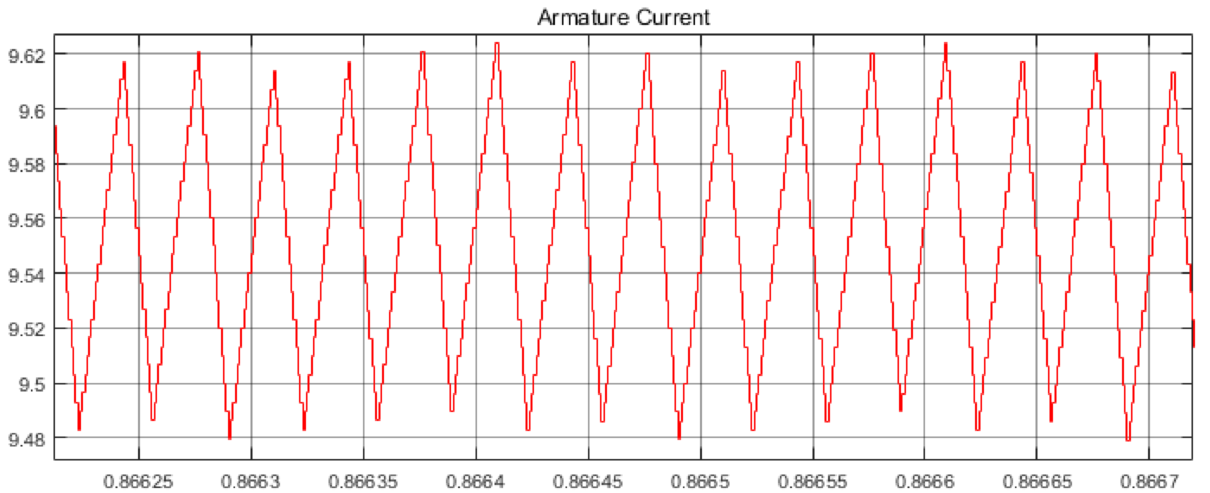

Figure 10: Armature Current with Zoom

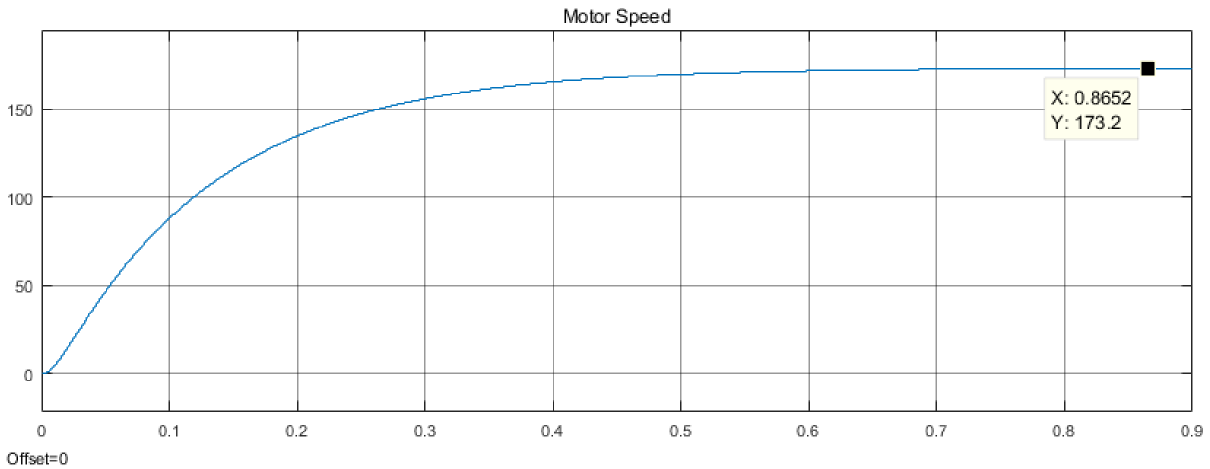

Figure 11: Motor Speed Graph

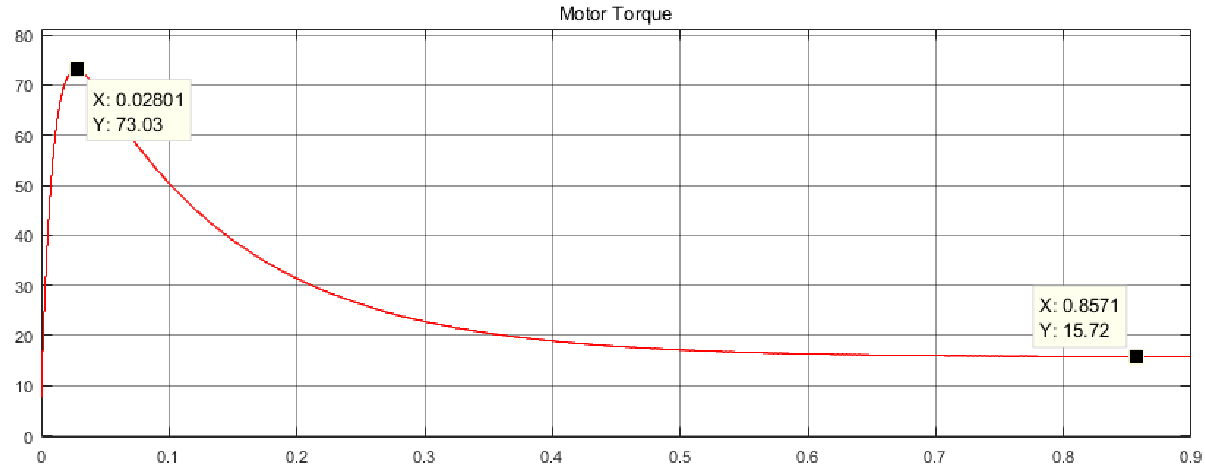

Figure 12: Motor Torque without Zoom

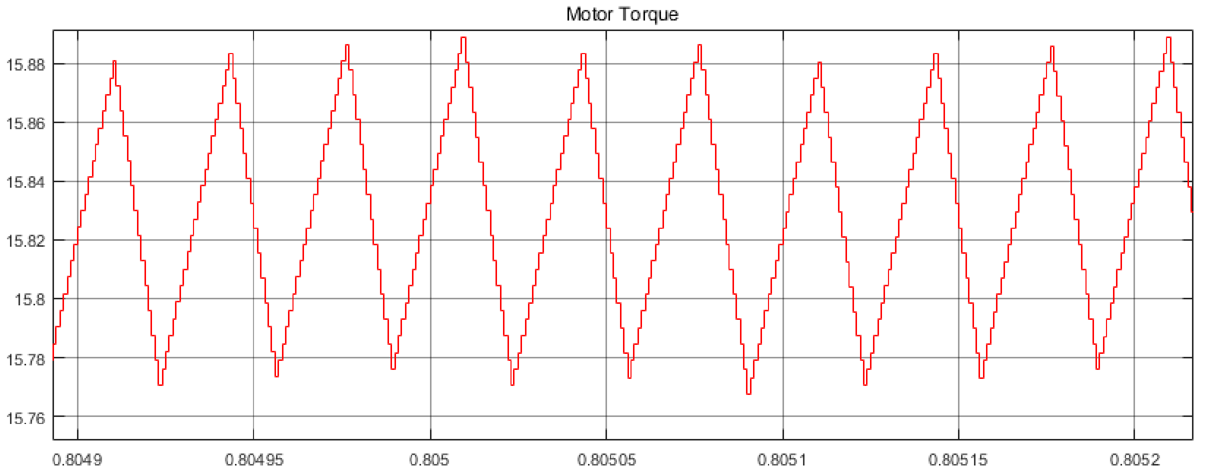

Figure 13: Motor Torque with Zoom

Now, combining the chopper circuit with the rectifier constructed before, the motor is driven again with 60% duty cycle and now, the waveforms can be seen below.

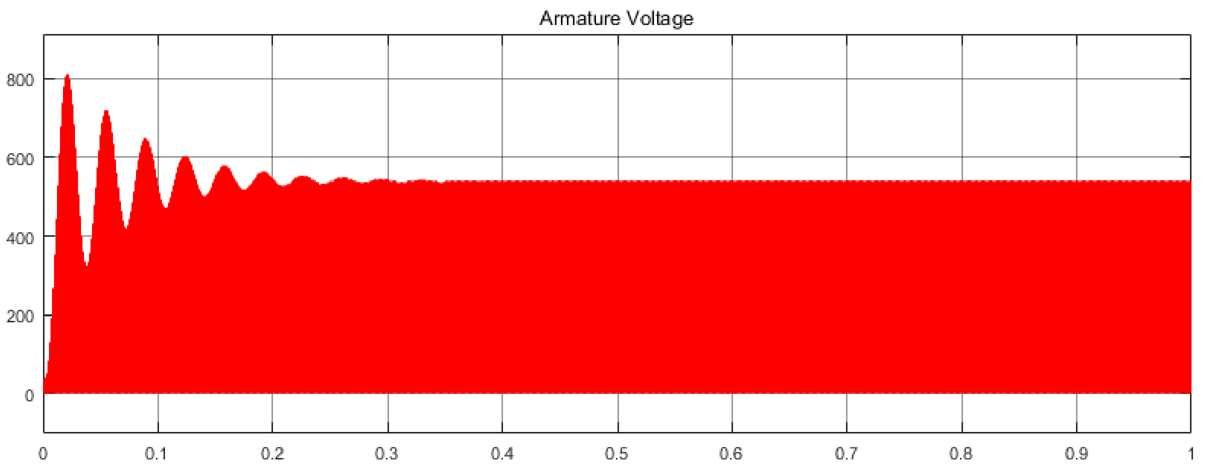

Figure 14: Armature voltage top view

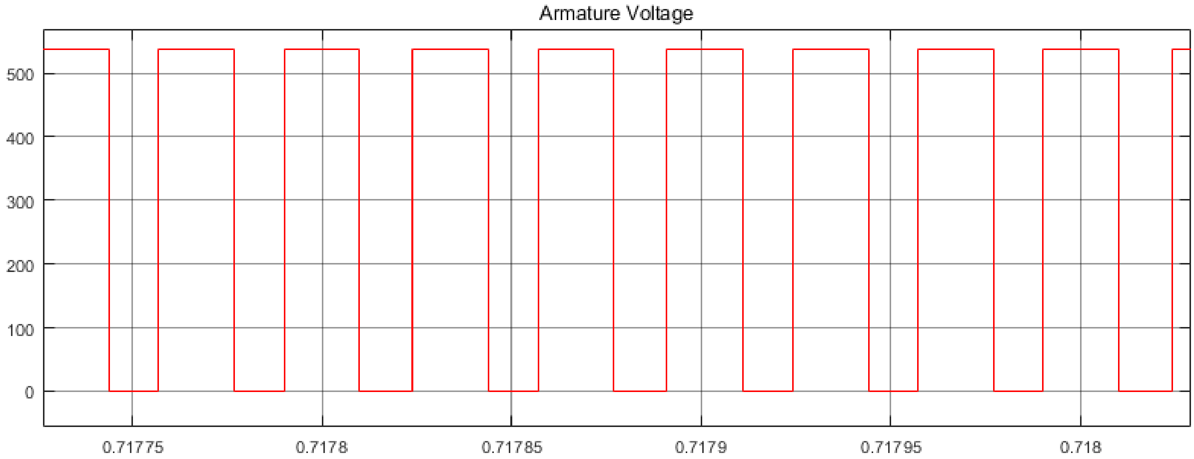

Figure 15: Armature voltage zoomed view

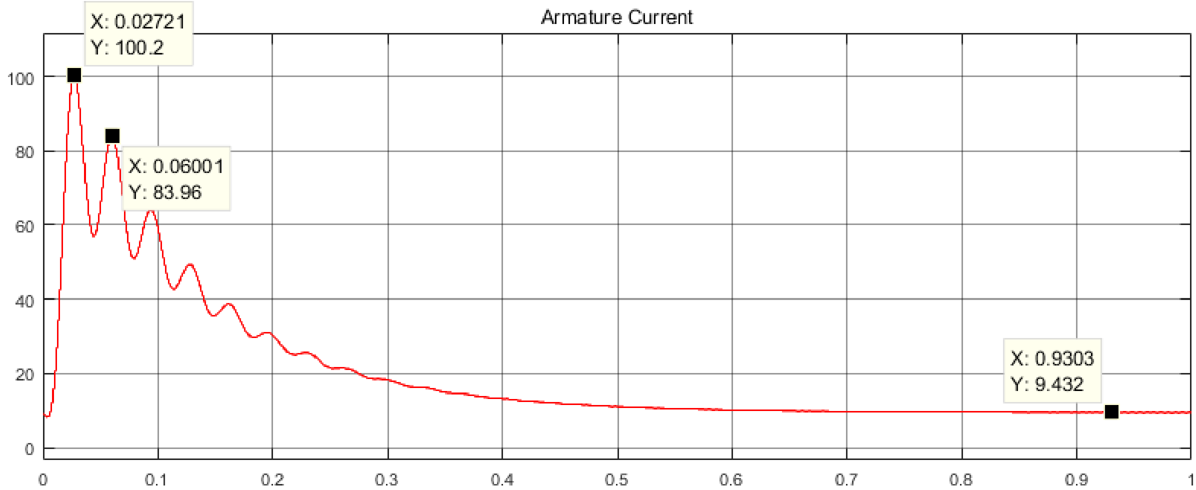

Figure 16: Armature Current top view

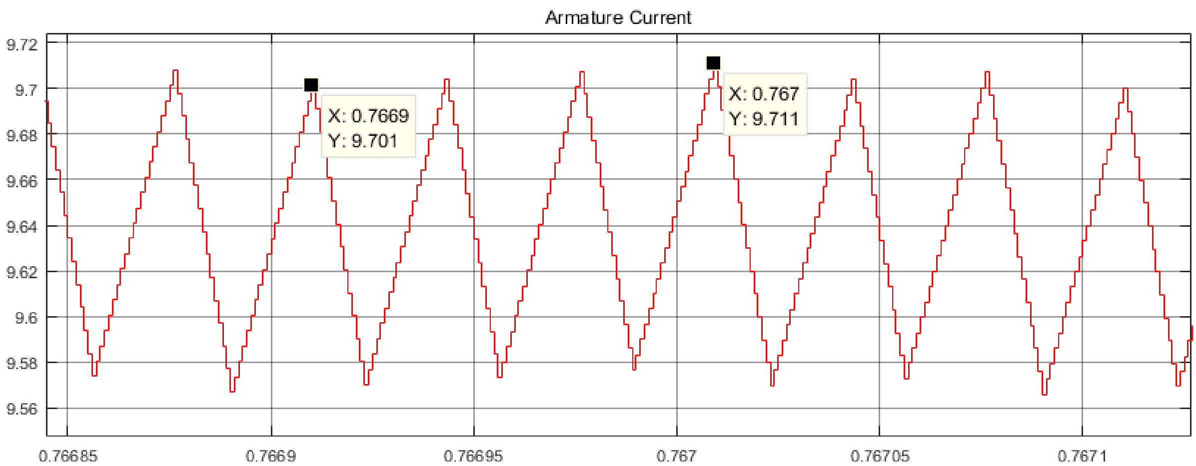

Figure 17: Armature Current zoomed view

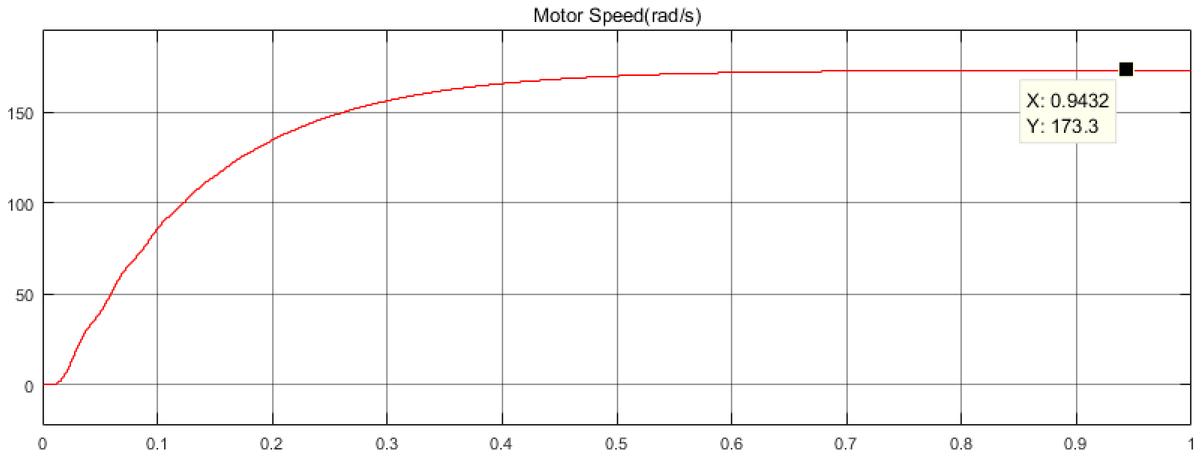

Figure 18: Motor Speed

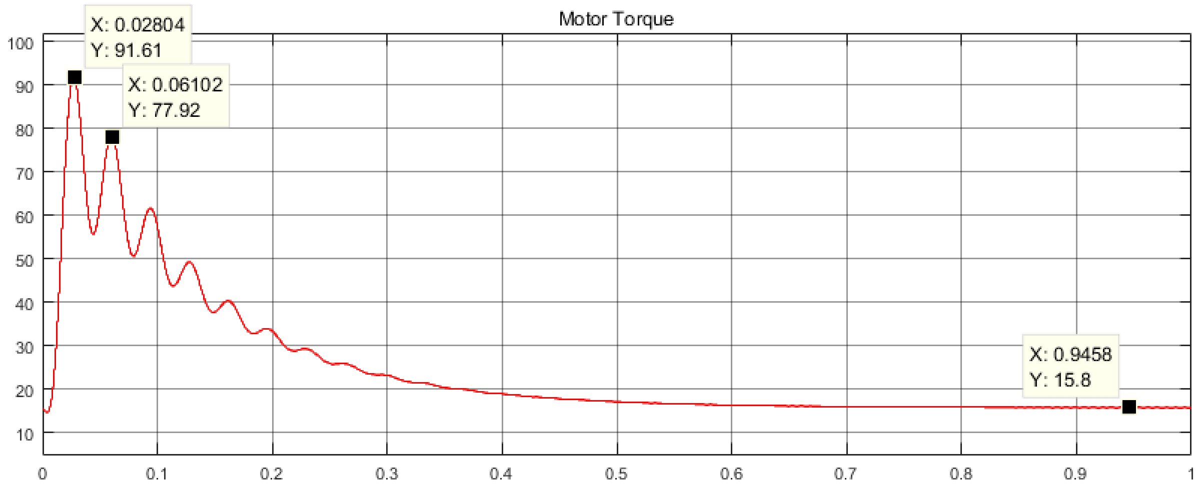

Figure 19: Motor Torque

Since the filter capacitor and inductor did not reach the steady state values we observe oscillations at the beginning. The oscillations seen in Figure 16 occurred at cut-off frequency of the LC filter and its magnitude gets lower as approaching the steady state. As seen in Figure 17, we have small continuous ripples basically occurred because of the switching. As seen on that figure, the ripples are in switching frequency. Therefore, we observe this oscillation in DC-source simulation also, Figure 10. At the steady state, two simulations give the same results.

PART C – OPEN LOOP CONTROL

For the following simulations in this part, the initial voltage of the capacitor is set to steady state value to get rid of oscillations in the beginning.

Forward Motoring at Rated Speed

$T = I_a * K_a$

$E_a = \omega * K_a$

$V_t = E_a + I_a * R_a$

$$T = \frac{V_t}{R_a} * K_a - \frac{\omega}{R_a} * {K_a}^2$$

$$V_t = V_{rectified} * D$$

$$D = \frac{T * \frac{R_a}{K_a} + \omega * K_a}{V_{rectified}}$$

$$D = 0.6465 \; for \; rated \; speed \; and \; load \; torque$$

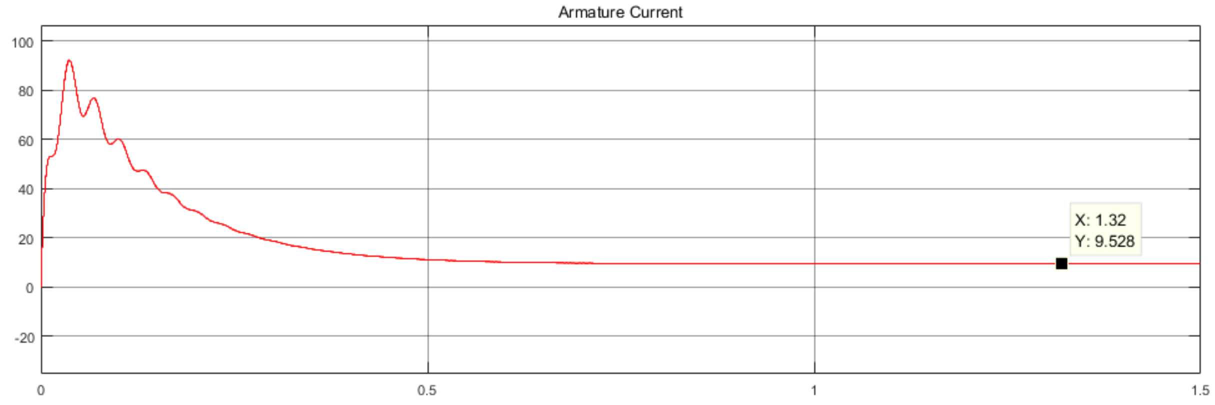

Figure 20: Armature Current

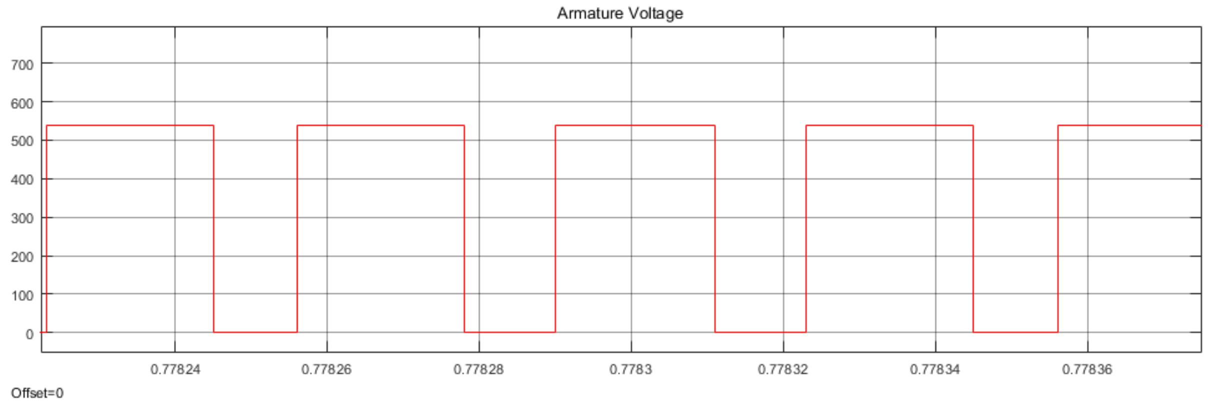

Figure 21: Armature Voltage

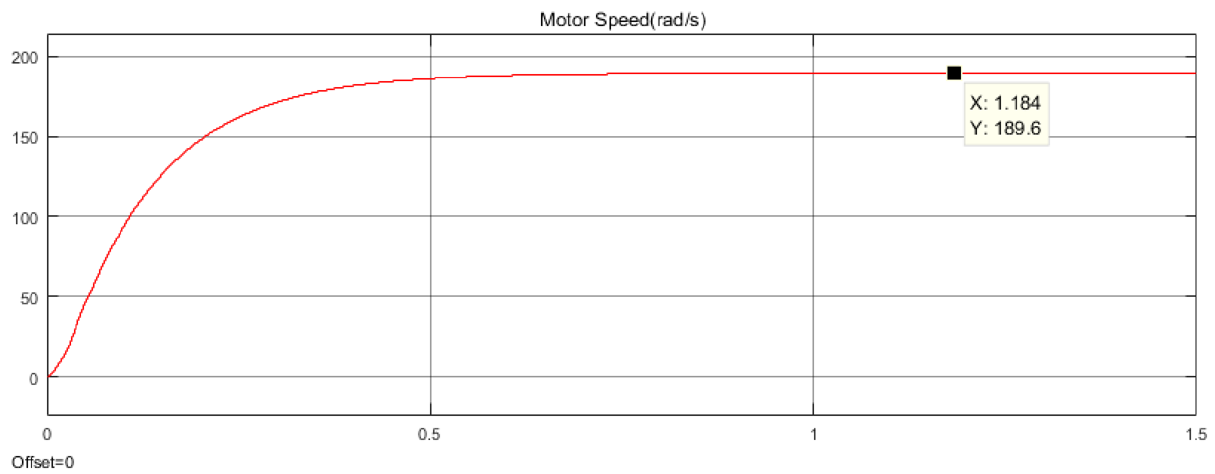

Figure 22: Motor Speed

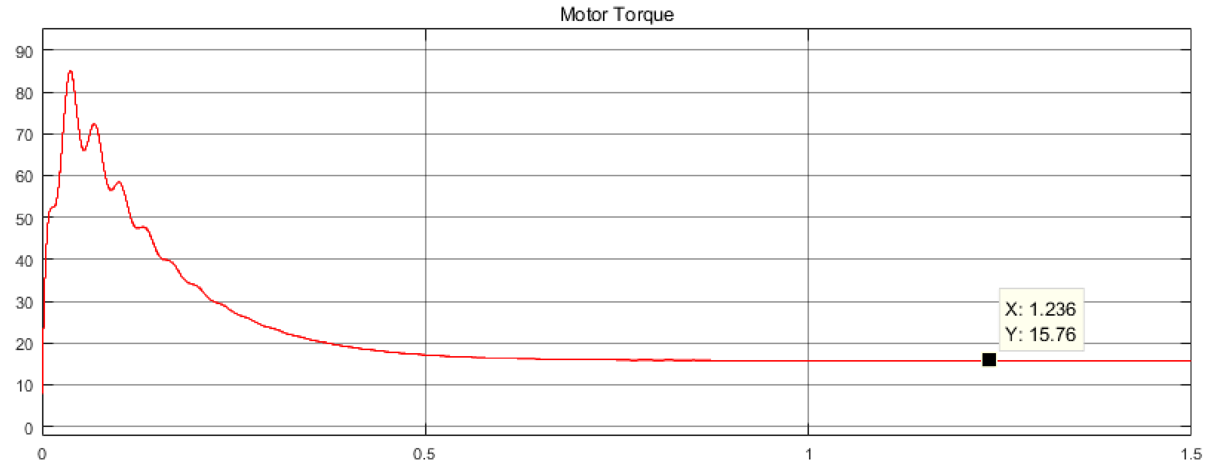

Figure 23: Motor Torque

Now, using the torque and speed, the duty cycle is calculated and applied to the motor driver. As seen on the graphs, after a couple of transient moments, the rated values are obtained. This is the point for this applied voltage where the torque and speed reaches steady state. The output values show the calculation is correct.

Rated Speed to Half Speed Step Response

$D = 0.3556\ for\ half\ of\ the\ rated\ speed\ and\ load\ torque$

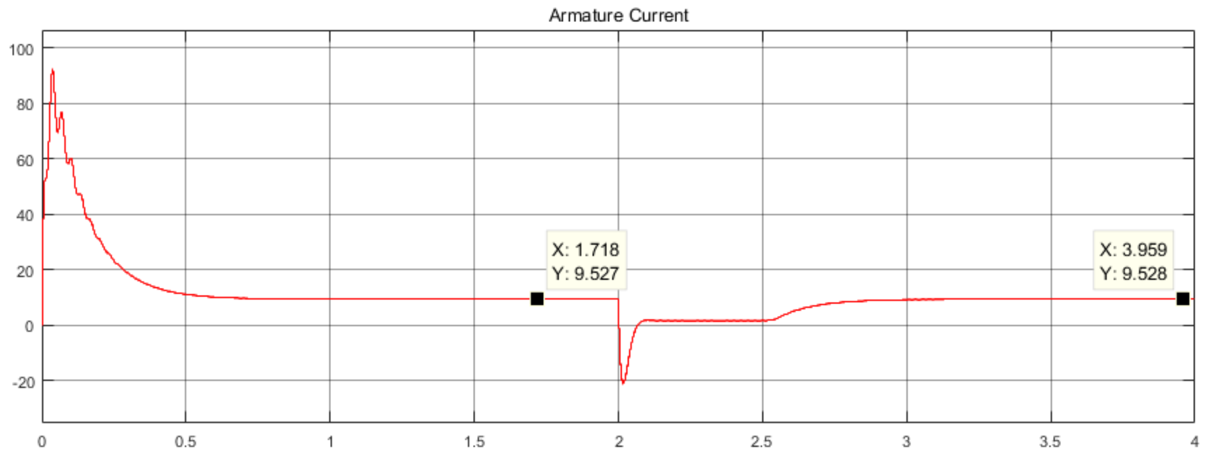

Figure 24: Armature Current

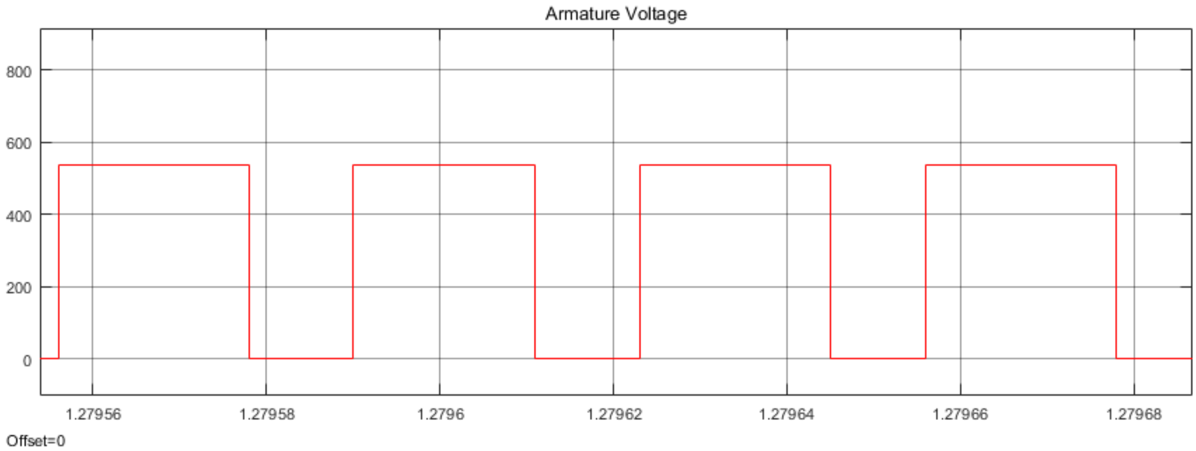

Figure 25: Armature Voltage before duty cycle step change

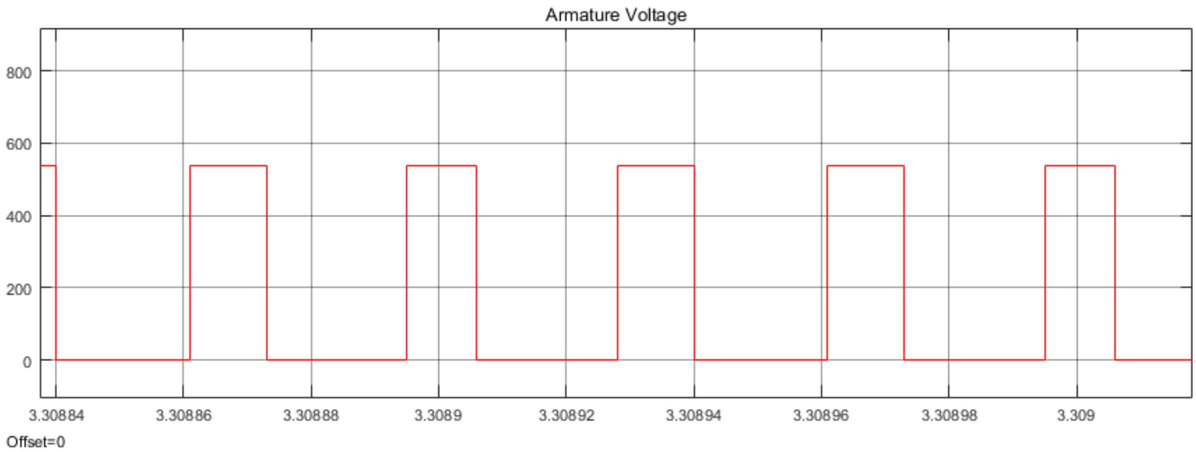

Figure 26: Armature Voltage after duty cycle step change

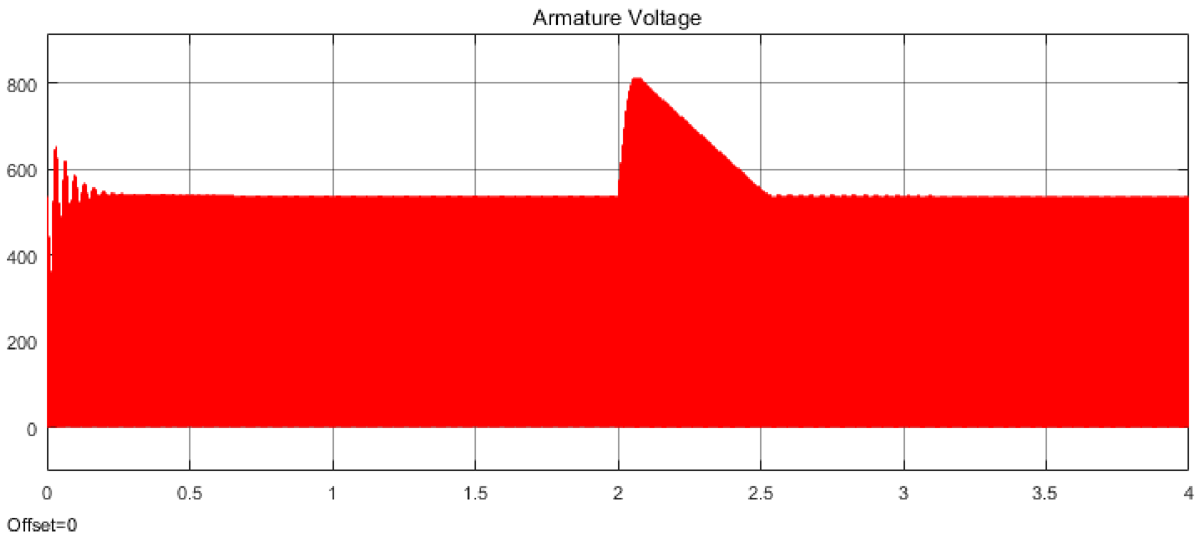

Figure 27: Armature Voltage top view

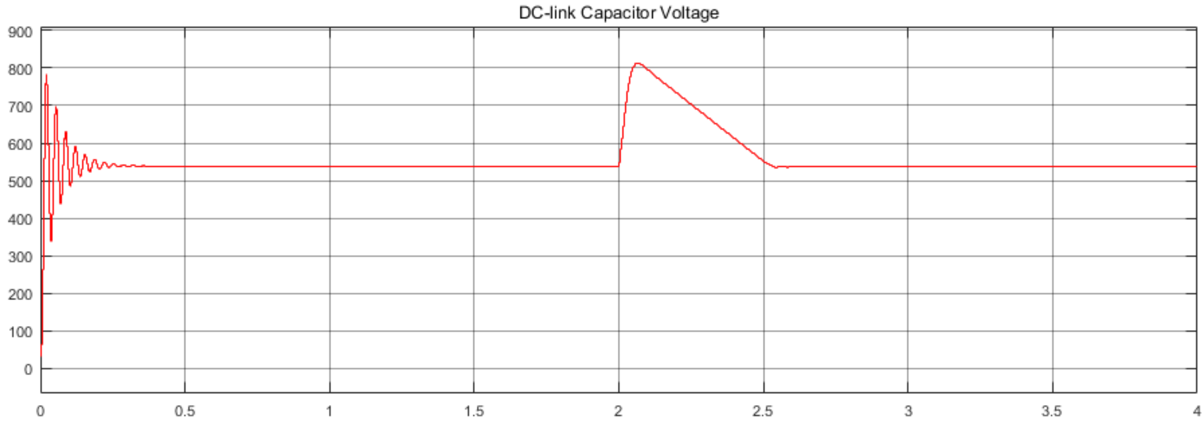

Figure 28: DC-link Capacitor Voltage

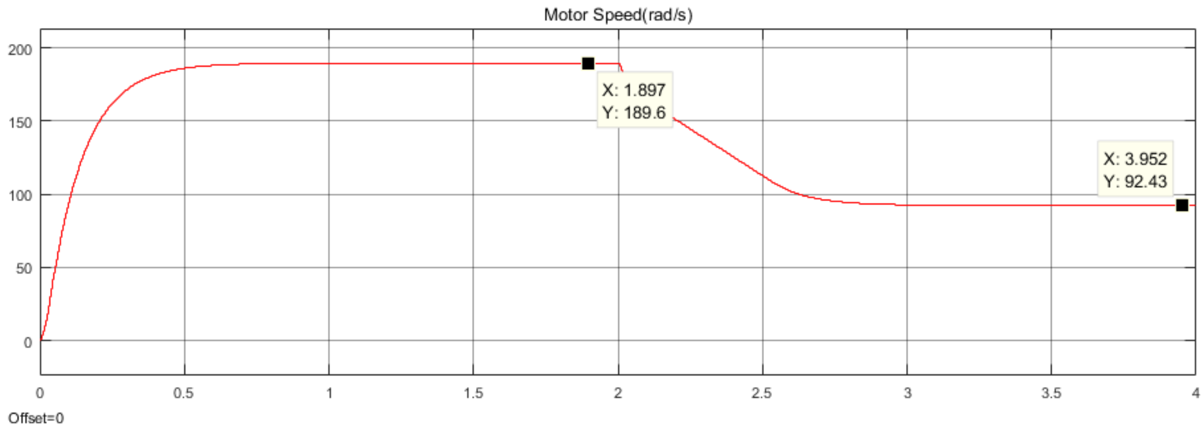

Figure 29: Motor Speed

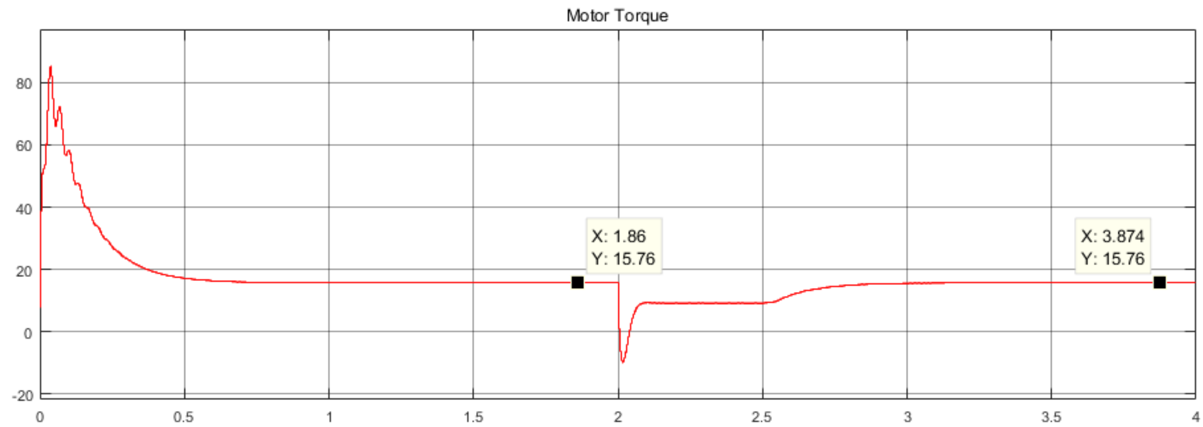

Figure 30: Motor Torque

As seen on the graphs, during the transient time the motor operates in generation region; that is, the power flows from motor to source side. Therefore, we observe an expansion on DC-link capacitor voltage. During the whole operation the motor operates in two quadrants: forward-motoring mode and generation mode. At the transient moment, the torque goes negative and resets again to the positive rated value.

PART D – DYNAMIC BRAKING

As we observe the braking characteristics, DC –link capacitor voltage in Figure 31 and braking torque in Figure 32, we see a deviation on these graphs. We observe that at the moment of the change, DC – link capacitor voltage increases above 800V. Also, we observe that the torque goes to negative for a short time. The stress on the transistors is proportional to the DC – link capacitor voltage, so unless the energy transferred to the capacitor side is dissipated on a resistor it will increase the stress on the transistors. Also dissipation of the power on the circuit can increase the temperature which also possibly harm the components. Moreover, the torque which goes to negative for a moment, the rapid change, may cause an oscillation on the load side. Therefore, the power should be dissipated on a resistor for healthy operation.

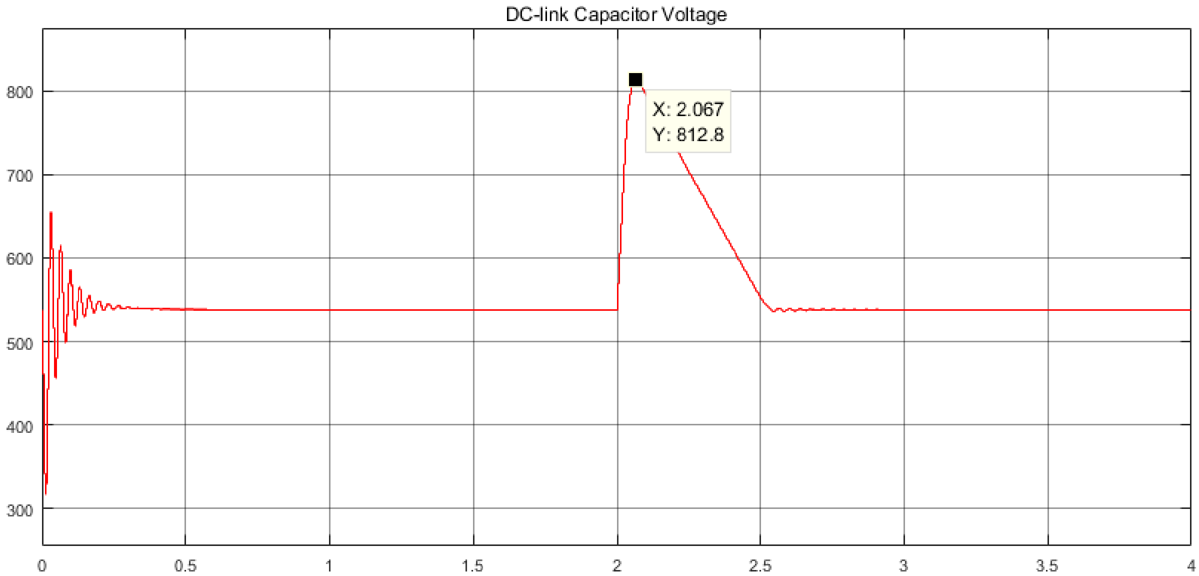

Figure 31: DC - link Capacitor Voltage

The nominal output voltage average is 537.8V, so the braking resistor will be dealing with larger voltage. The control mechanism of the braking resistor is set such that it produces 0%-100% duty cycle range between 580V-620V DC – link capacitor voltage. Therefore, the braking resistor voltage will be up to 620V, so it is chosen with respect to the real braking resistor values.[1] This is a 13-ohm resistor which can dissipate 60HP power with 50% duty cycle. In our case, the maximum braking resistor current will be 47.7A which is equally produces 39.65HP. It shows that we are in safe region. An IGBT is connected in series with the braking resistor and this IGBT is controlled via a duty cycle applied to the gate of the IGBT.

[1] (POWEROHM RESISTORS, 2017)

Figure 32: The dynamic braking resistor control unit

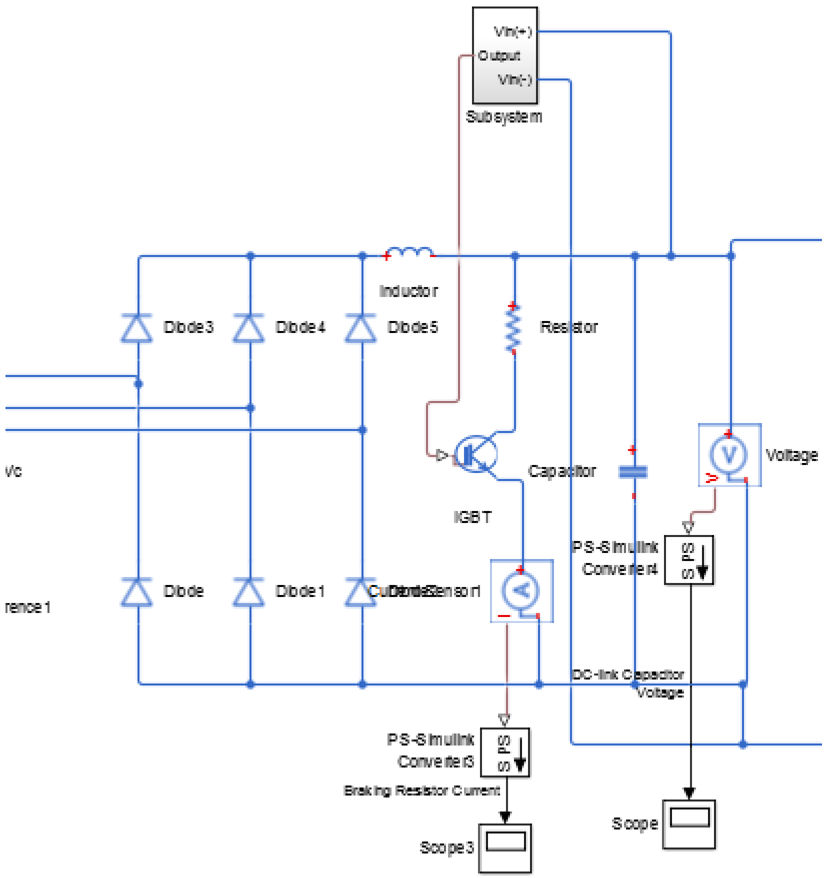

Figure 33: The circuit diagram which shows how the braking resistor is connected

The obtained results are the following ones.

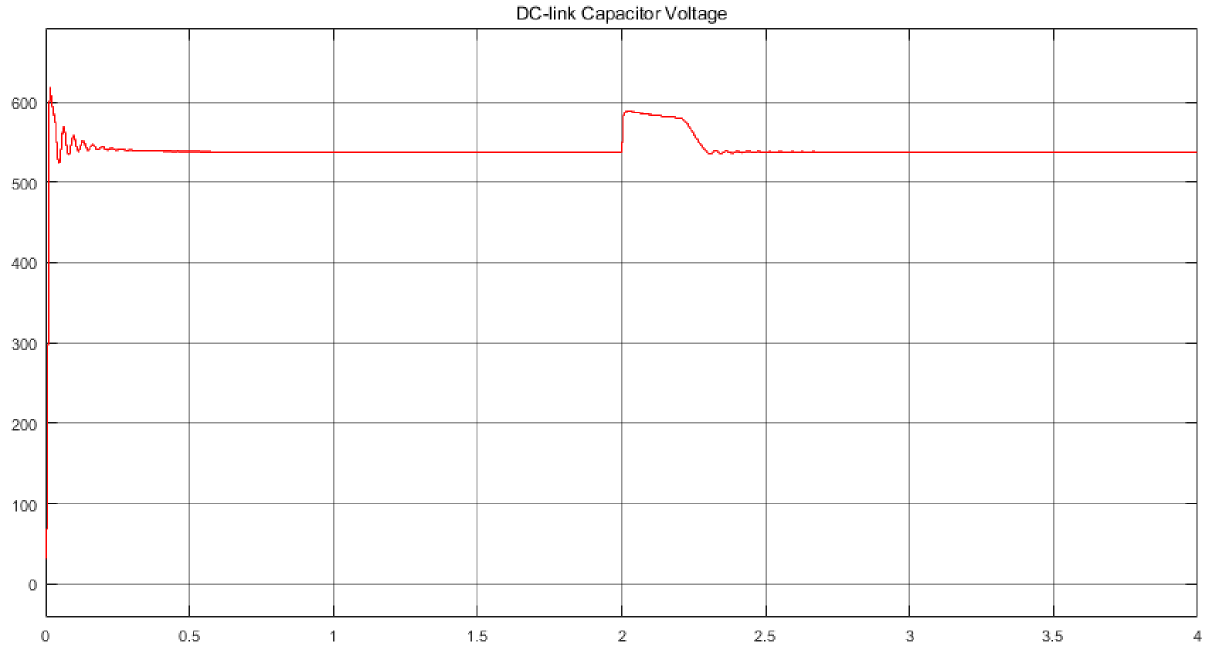

Figure 34: DC - link capacitor voltage

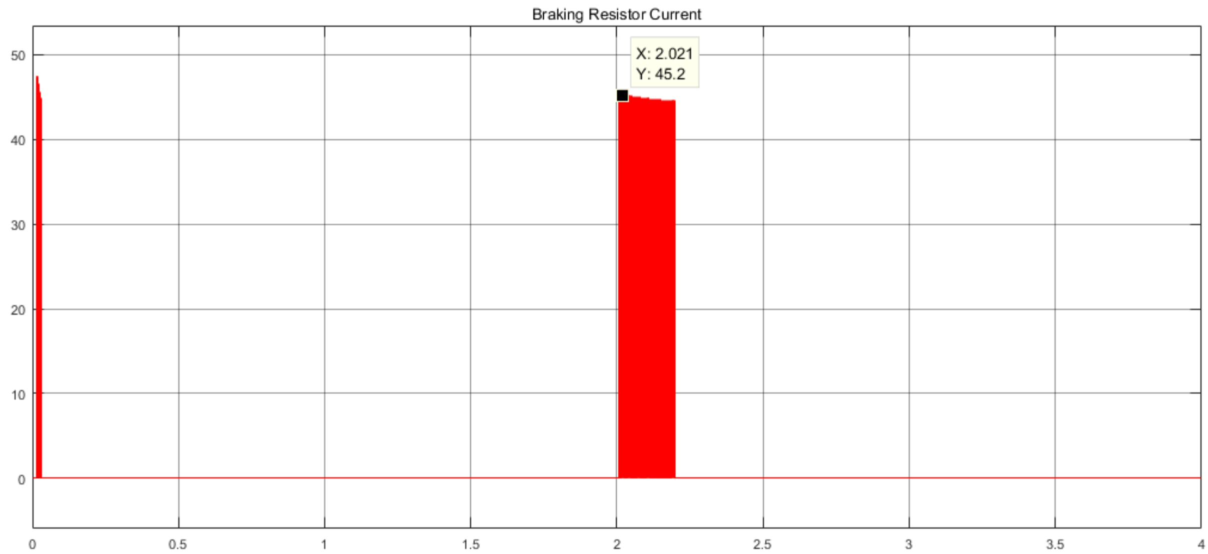

Figure 35: Braking Resistor Current

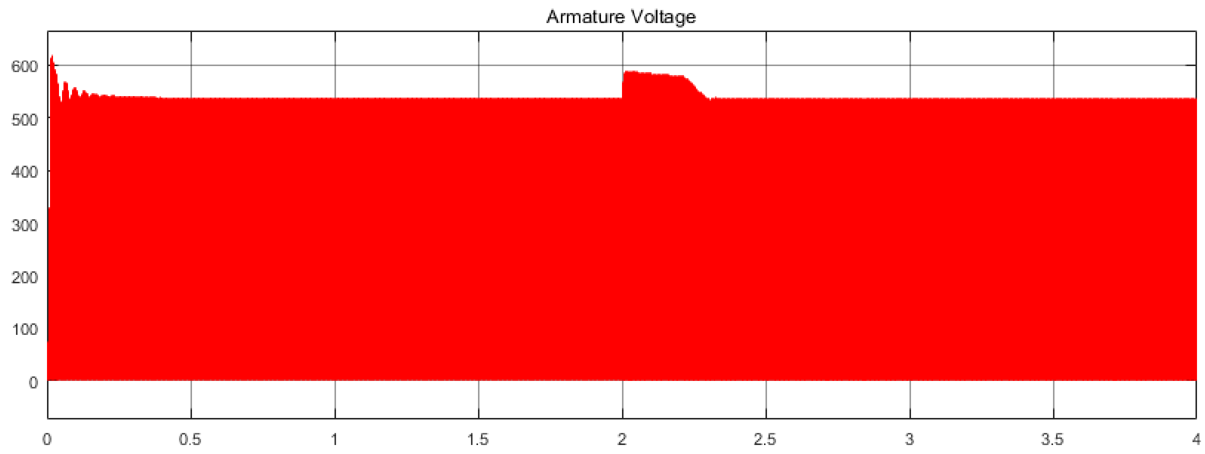

Figure 36: Armature Voltage

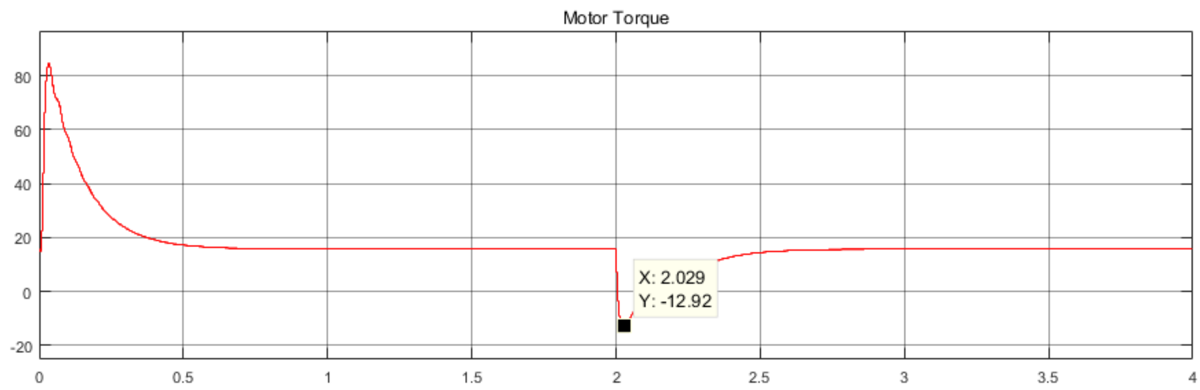

Figure 37: Motor Torque

As we observed on the results, the dynamic braking makes lower the stress and DC – link capacitor voltage is below 750V during the operation.

PART E – CLOSED LOOP CONTROL

PID controllers are used to settle the parameters to desired value in desired amount of time with acceptable oscillations. In motor driver applications, PID controllers are used for controlling the motor speed and armature current. The armature current is controlled because unexpected values can harm the motor and also a limit for acceleration might be wanted. The speed is controlled to use the motor with required speed.

PID is a type of controller which takes the error of the controlled parameter as an input and prepare an output to control the system. As knows, PID controllers consist of three elements proportion, integration and derivation. The proportional constant symbolizes how fast the parameter reached the desired value at the startup and integration constant is used to settle at just on the target and derivation constant is used for lowering the oscillations.

PI Type Current Controller

In this part, a PI controller is used to control the armature current to prevent exceeding %150 of the rated value. The proportional constant is set as 100 for rapid acceleration, and the integration constant set as 0.1 and the oscillations are not problematic. Also a saturation between 0 and 1 is set at the output side of PID to obtain meaningful results. Corresponding waveforms are given below.

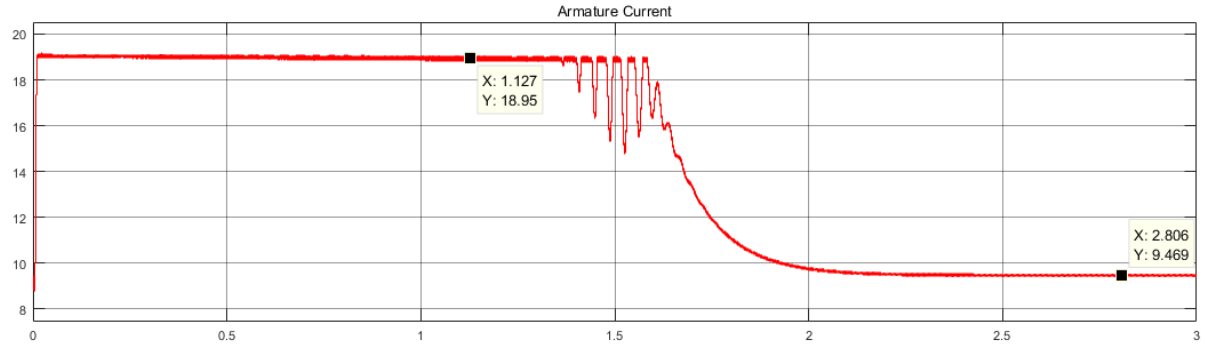

Figure 38: Armature current graph top view

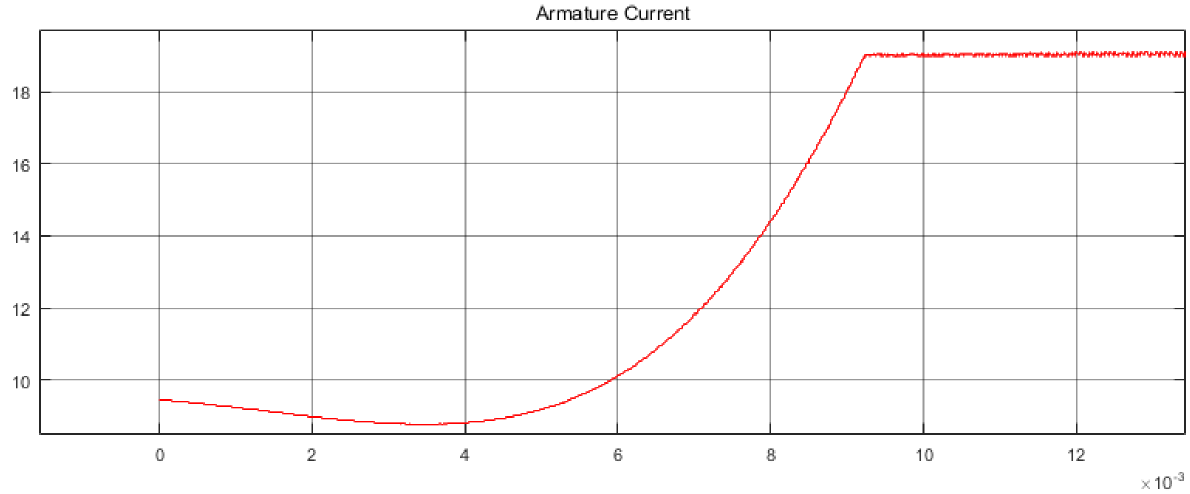

Figure 39: Armature Current graph starting time

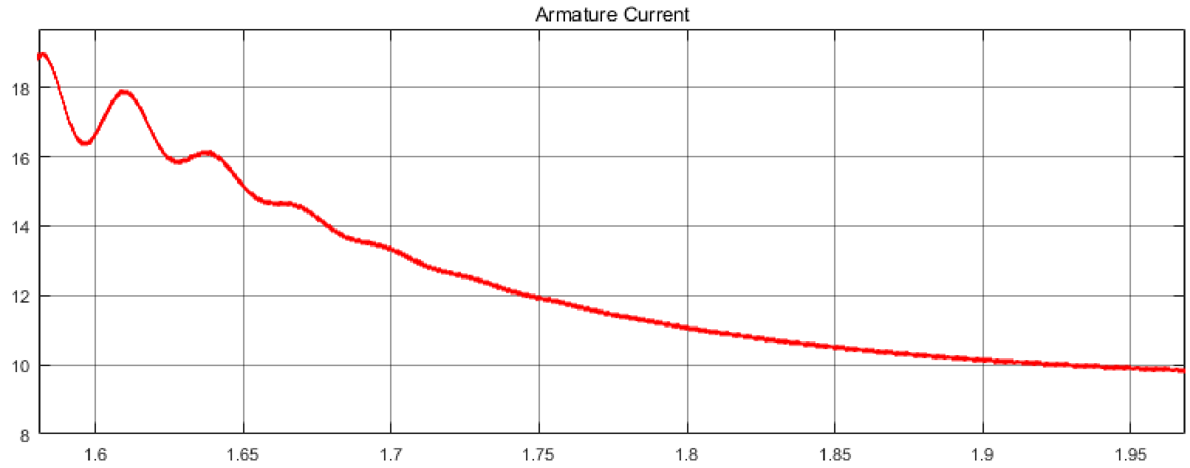

Figure 40: Armature Current Transient Time

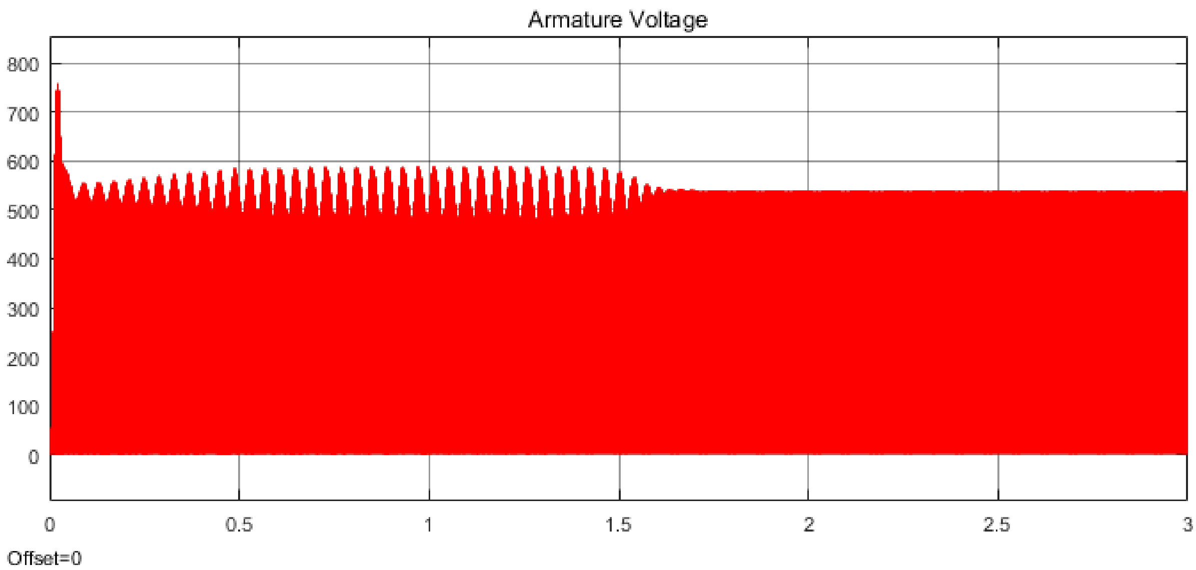

Figure 41: Armature Voltage Top View

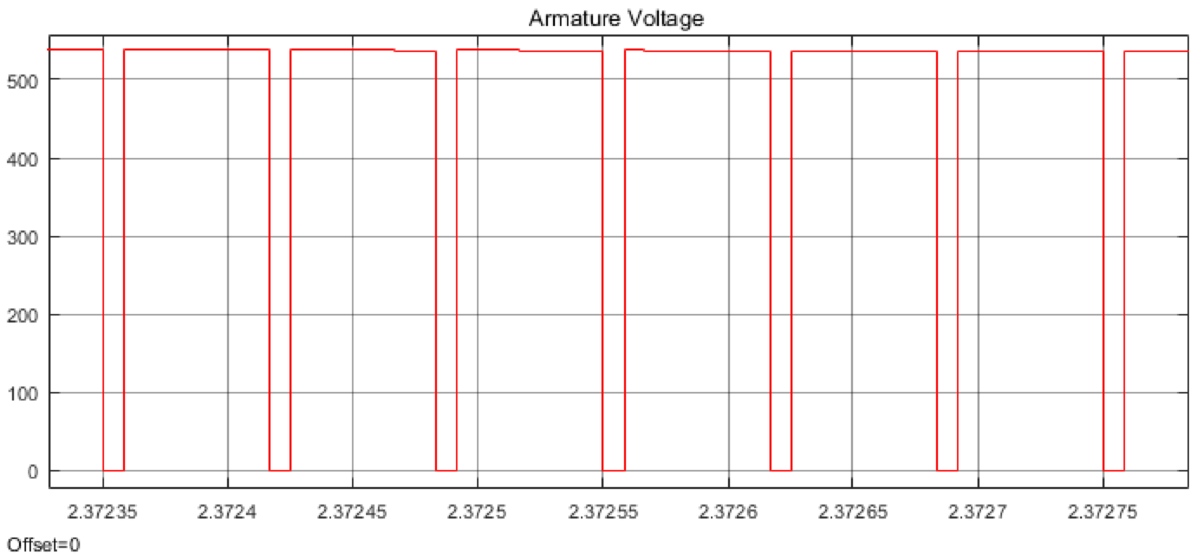

Figure 42: Armature Voltage at Steady State, duty cycle 88%

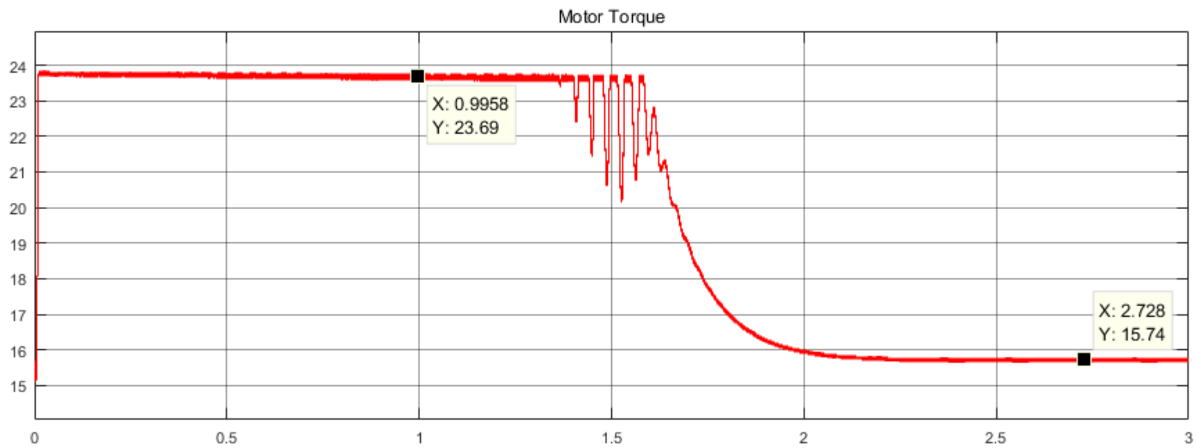

Figure 43: Motor Torque in N.m

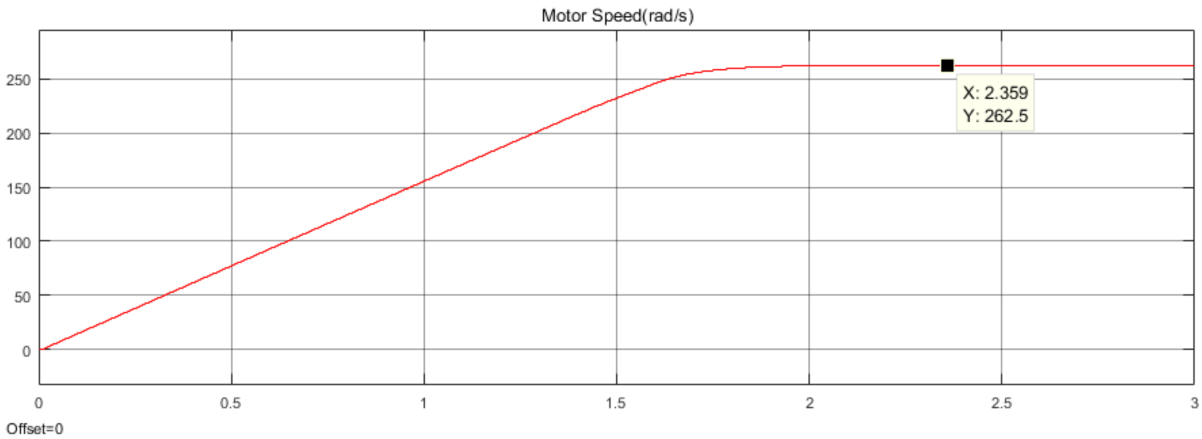

Figure 44: Motor Speed (2500 rpm)

Hysteresis Current Controller

Hysteresis controller is a one which produces 1 or 0 with respect to comparison of signal and reference points. In this model, the armature current is compared with on and off reference values and output is given as duty cycle. To implement hysteresis controller, the relay component of the Simulink is used. The corresponding waveforms are the following ones:

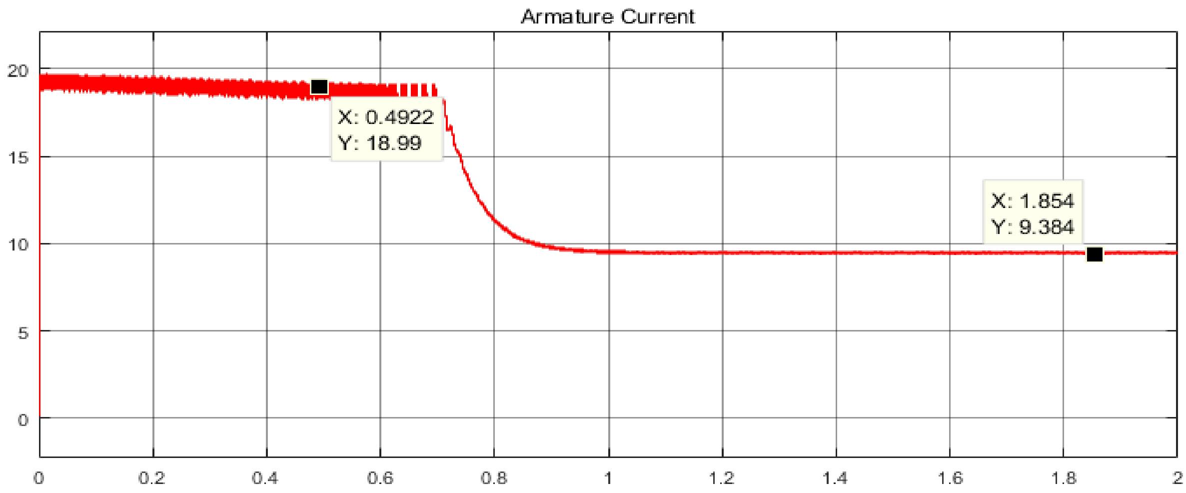

Figure 45: Armature current top view

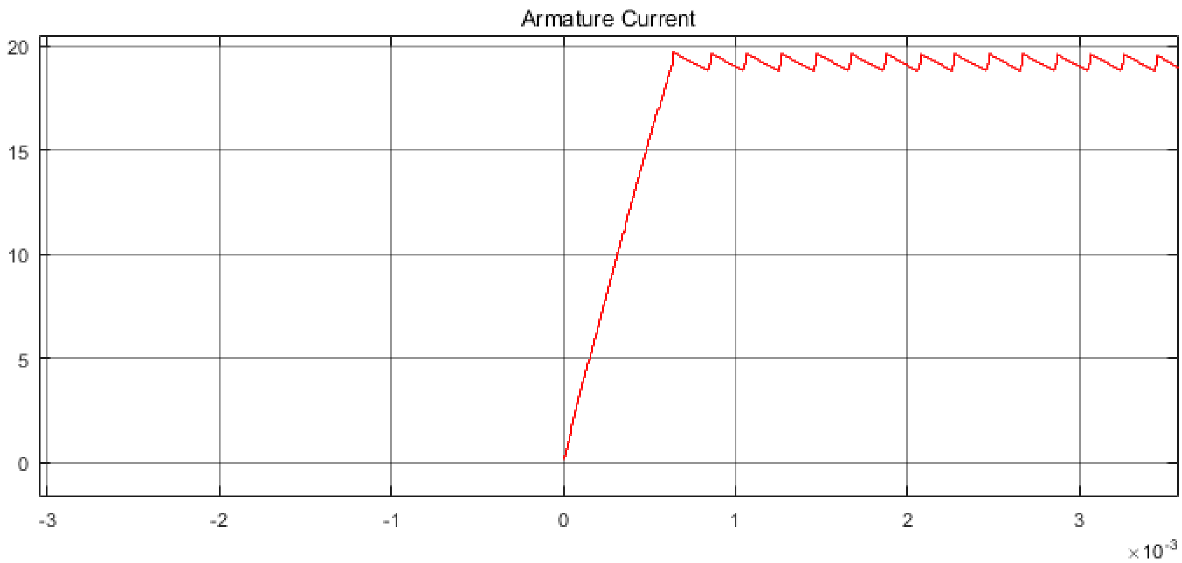

Figure 46: Armature current starting view

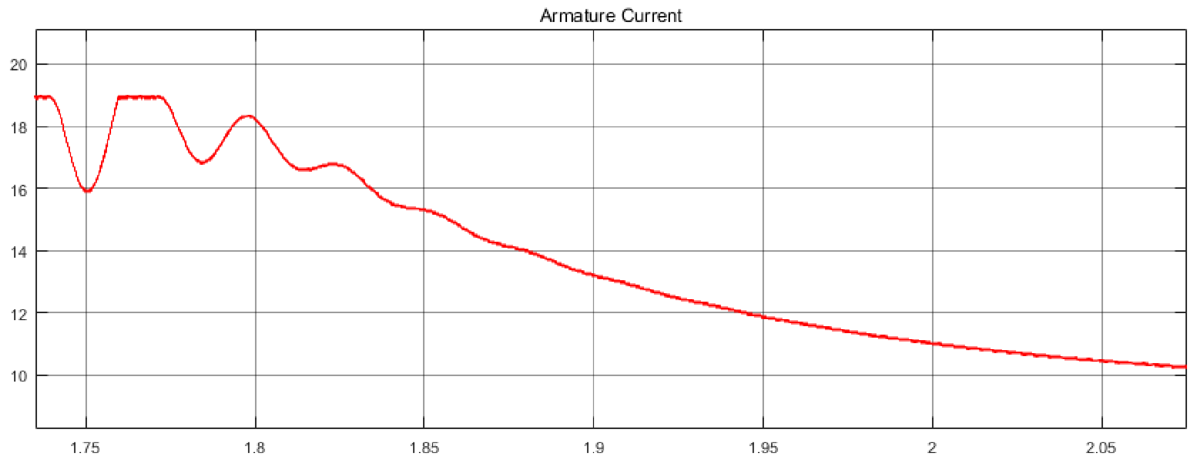

Figure 47: Armature current transient time

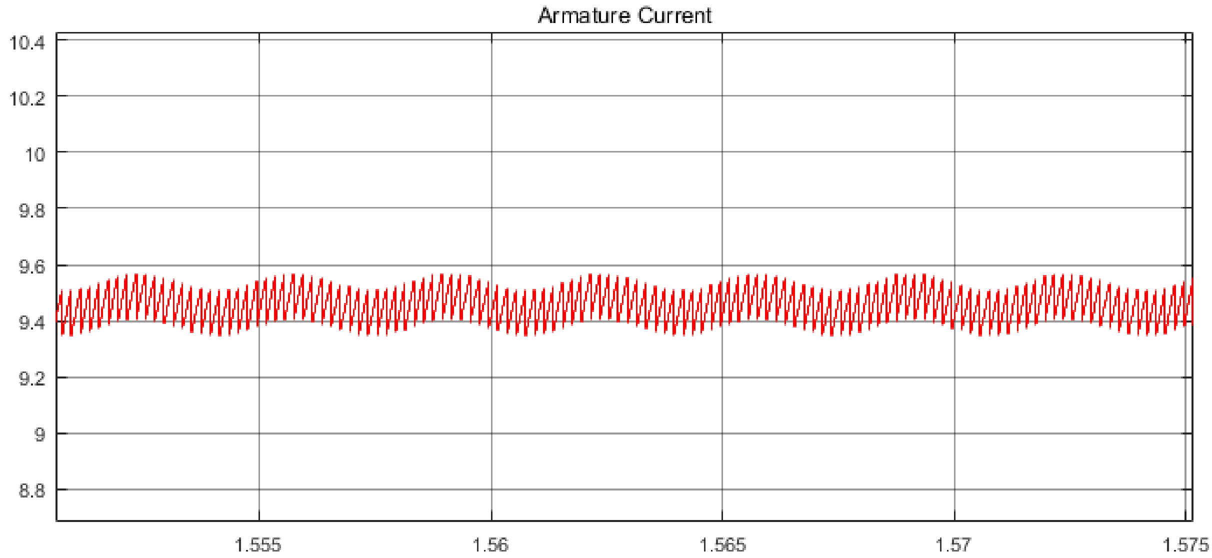

Figure 48: Armature Current Zoomed View

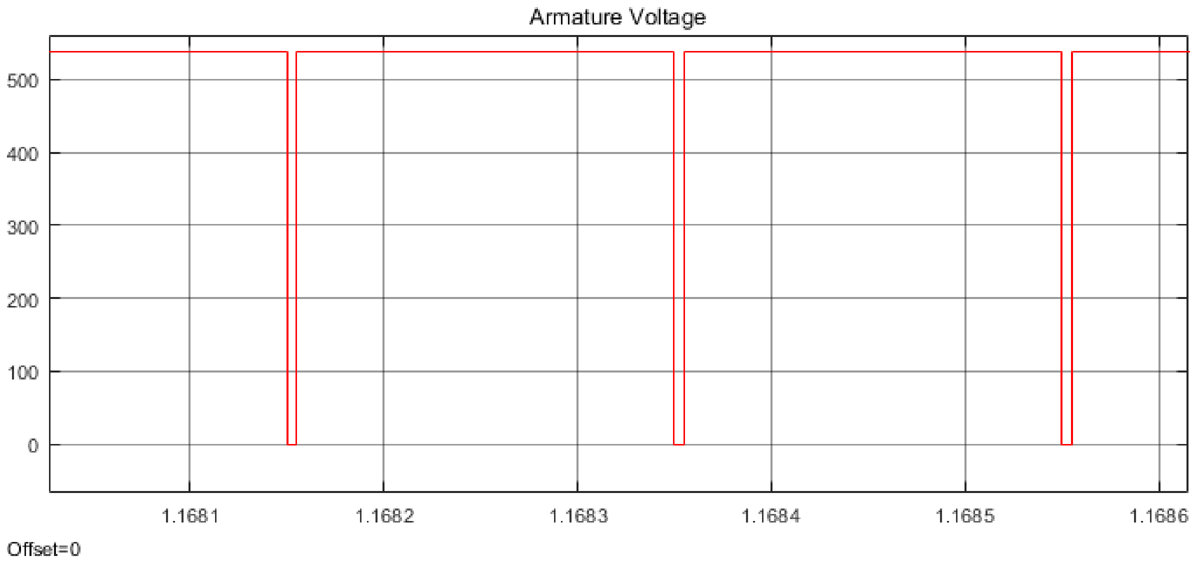

Figure 49: Armature Voltage steady state view

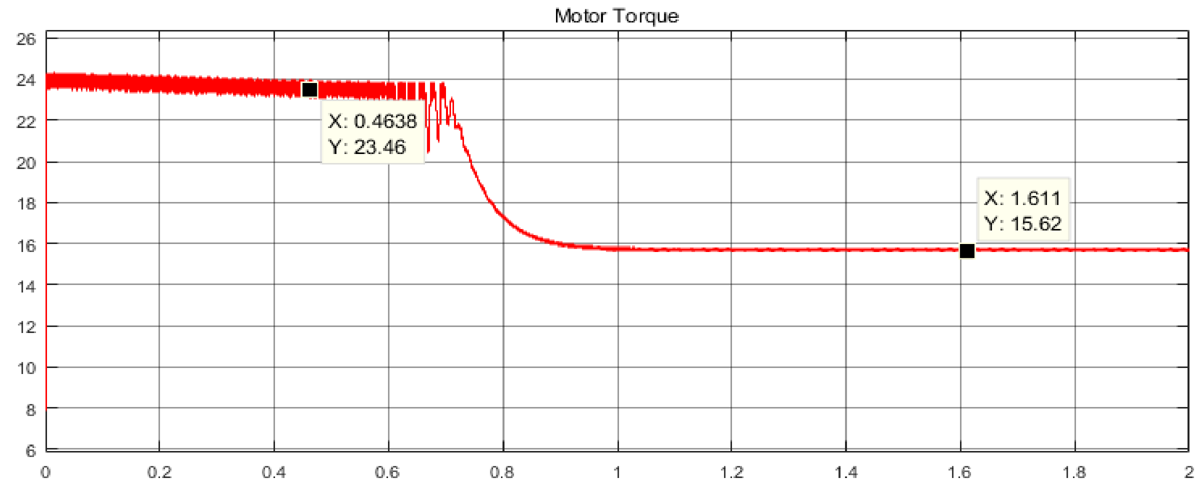

Figure 50: Motor Torque Graph

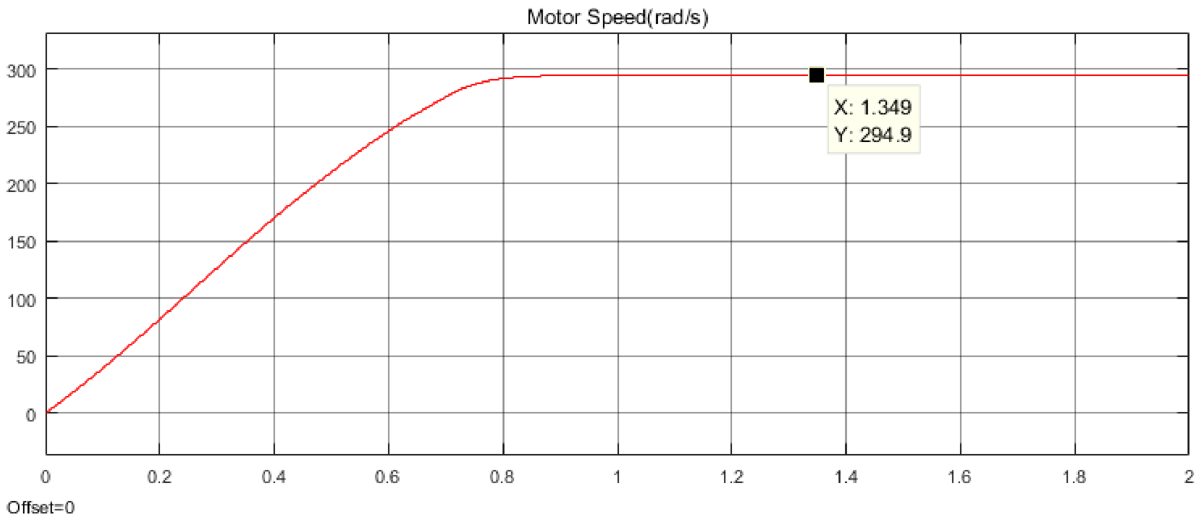

Figure 51: Motor Speed Graph (2816 rpm)

Comparison of PI Controller & Hysteresis Controller

Both controllers are run with a reference constant as 19. Hysteresis controller is advantageous for setting the maximum and minimum points, that is we can select the ripple limits. However, it is a straight forward which is basically ON/OFF. Therefore, if the controlled parameter changes rapidly, it would not be meaningful to use a hysteresis controller because it oscillates rapidly. Therefore, for applications with big inertia and sensitive control is not required, hysteresis controller can be beneficial. On the other hand, if a smooth transient is required and detailed controller is desired, one should use a PID controller with well-tuned constants. It should be also considered that implementation of the hysteresis controller is more simple than PID controller. In our case, we observe for the PID controller the current changes more smoothly as we observe this on the startup time figures which are Figure 37 and Figure 44.

PART F – SPEED CONTROLLER

Speed controller is implemented with a PI block whose output is connected to the reference input of the current controller.

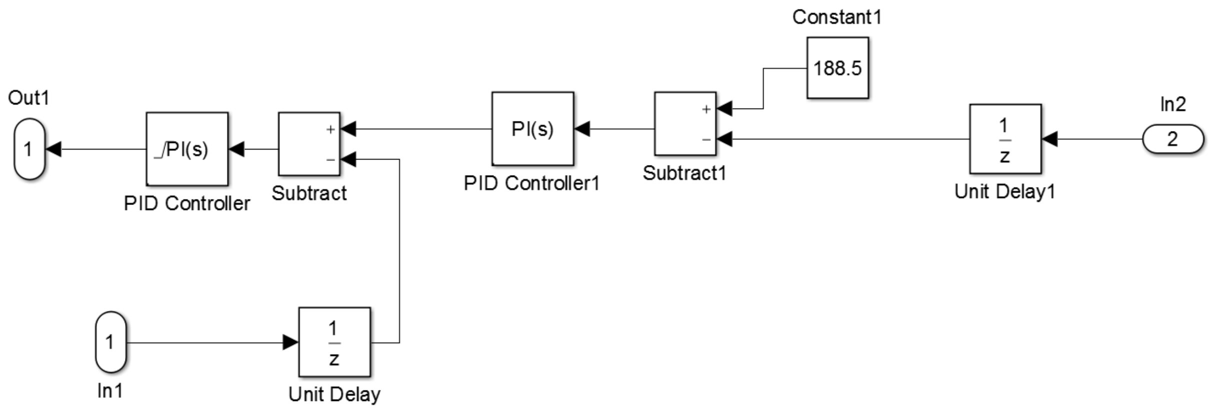

Figure 52: PI controller for speed and current

Here different than the current controller, the speed increases slowly from zero to rated speed. Therefore, the difference between reference and speed makes a huge effect on the current. Therefore, the proportional constant of the speed controller PI is set as 0.1 to obtain a current which not exceeds 150% of the rated current. Integration constant is set as 0.1 to get acceptable oscillations. This constant was also tried as 0.01 but this time it takes long time to reach steady state speed, therefore it is chosen as 0.1 again. The proportional constant is chosen such a low value because when the motor accelerates, the speed is much lower than reference and with a high proportional constant it makes a big effect on the current, and current exceeds the limit. Integration constant is selected such that the ripples are not distorting.

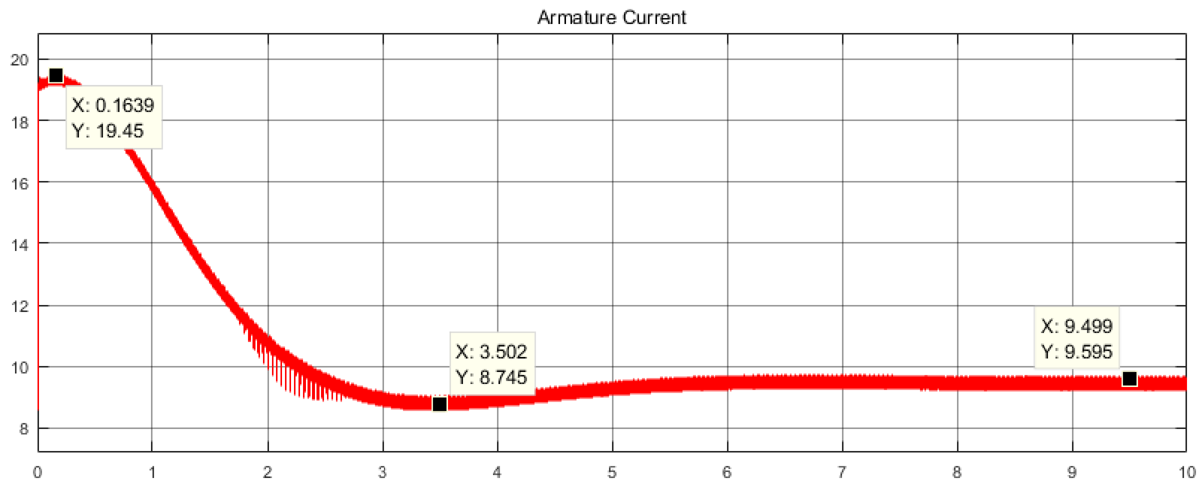

Figure 53: Armature Current Top View

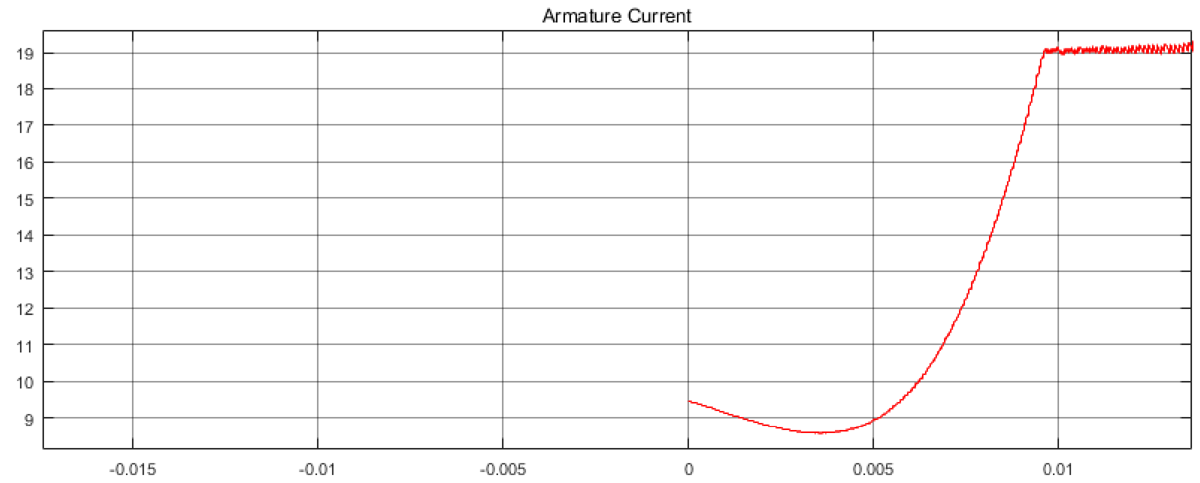

Figure 54: Armature current startup moment

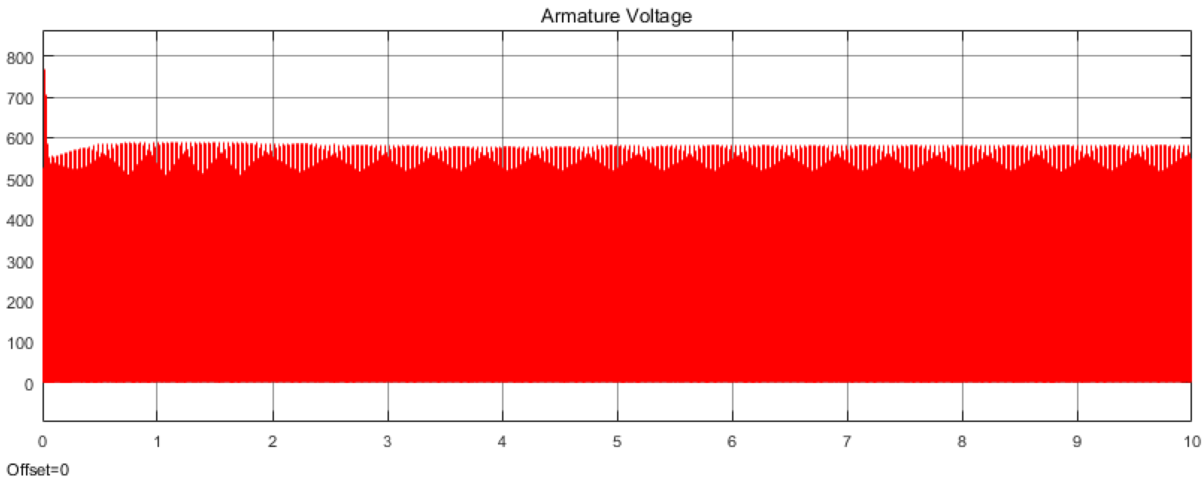

Figure 55: Armature Voltage Top View

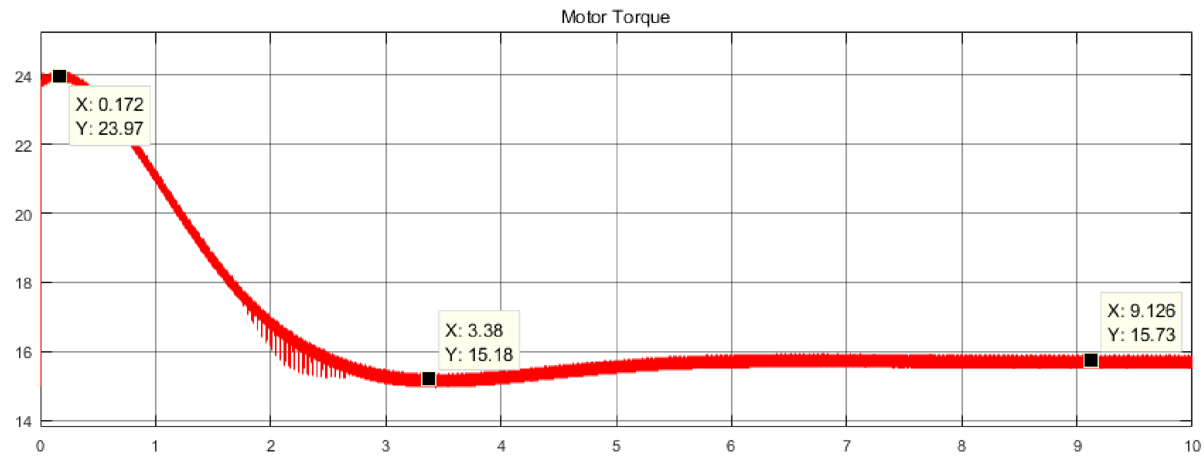

Figure 56: Motor Torque

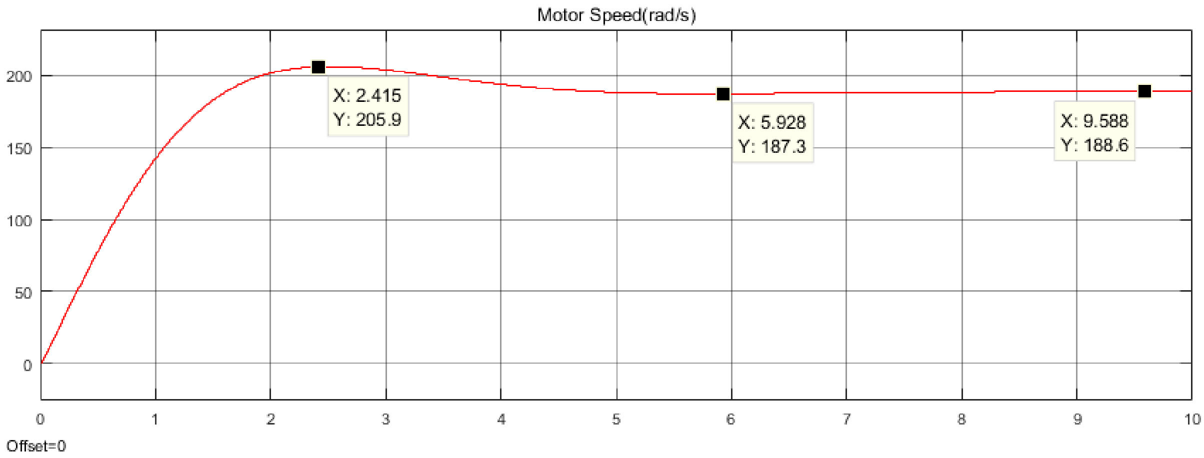

Figure 57: Motor Speed (1800 rpm steady state)

As seen on the plots, the current is in the limits while the speed approaches to rated speed. Different than the current controller, now we can control both current and speed. Oscillations are in the acceptable range. Controlling of the speed is important for proper operation and current control is important for limiting the current, so the operation stays as safe for all components.

The acceleration and deceleration graphs can be investigated with the following ones; the deceleration starts at t=15s.

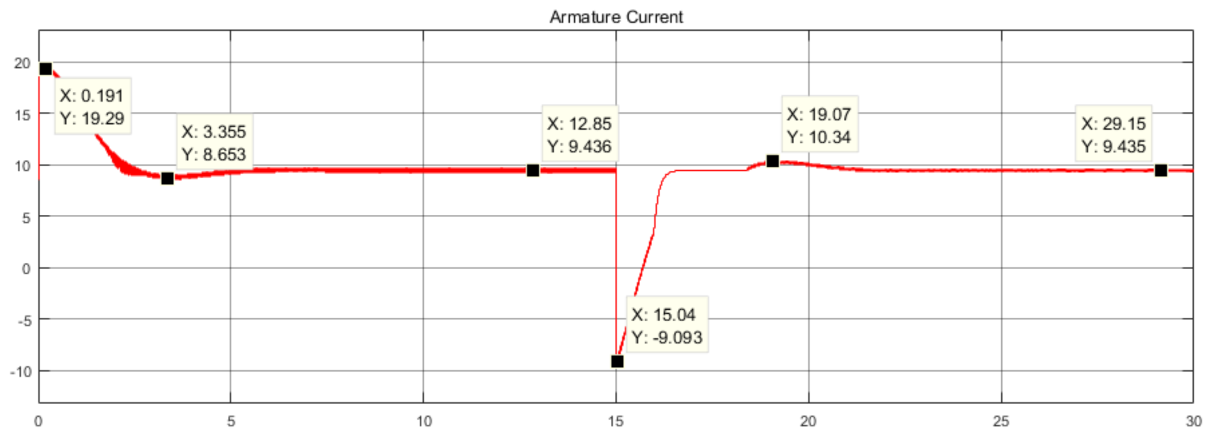

Figure 58: Armature Current

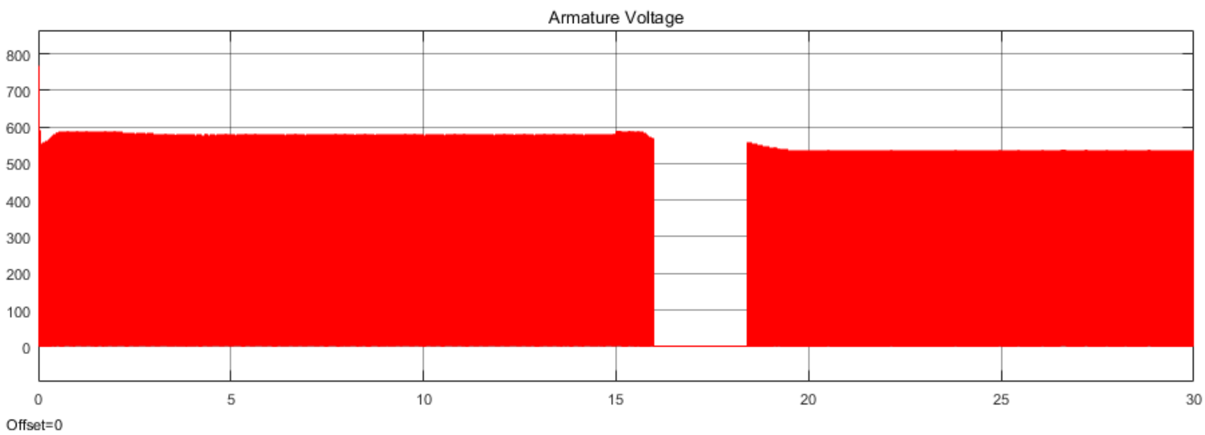

Figure 59: Armature Voltage

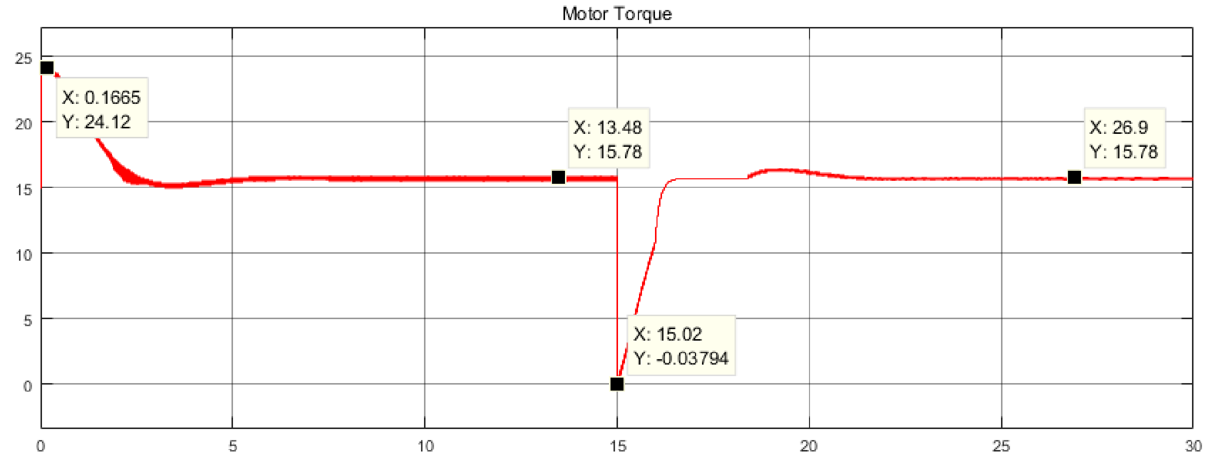

Figure 60: Motor Torque

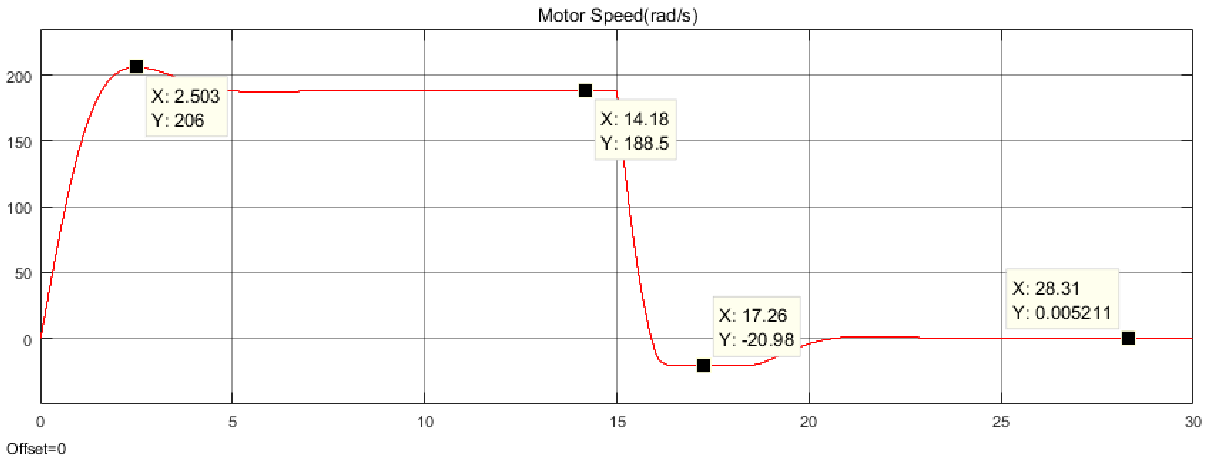

Figure 61: Motor Speed

As observed on this graphs, the PID controllers, speed and current controllers, are working well. At t=15s the speed reference is changed to 0 and without exceeding current limits the motor speed decreased and it stopped.

PART G – COMPONENT SELECTION

For this application, MOSFET is more suitable because it can operate higher frequencies and switching loss is less than IGBT. Also since it is an application in which DC voltage is less than 1kV, IGBT is not preferable. For chopper MOSFETs, IXYS's IXFH40N85X[2] MOSFET can be used. Since we used dynamic braking, the drain source voltage of the MOSFETs does not exceed 750V, and this selected MOSFET has a capability of blocking 850V. Also, it can conduct 40A current @125˚C and our current controller is adjusted such that the current does not exceed 20A, therefore the selected MOSFET is compatible with this application.

The rectifier diodes' voltage and current graphs are given below:

[2] (IXYS Corporation, 2016)

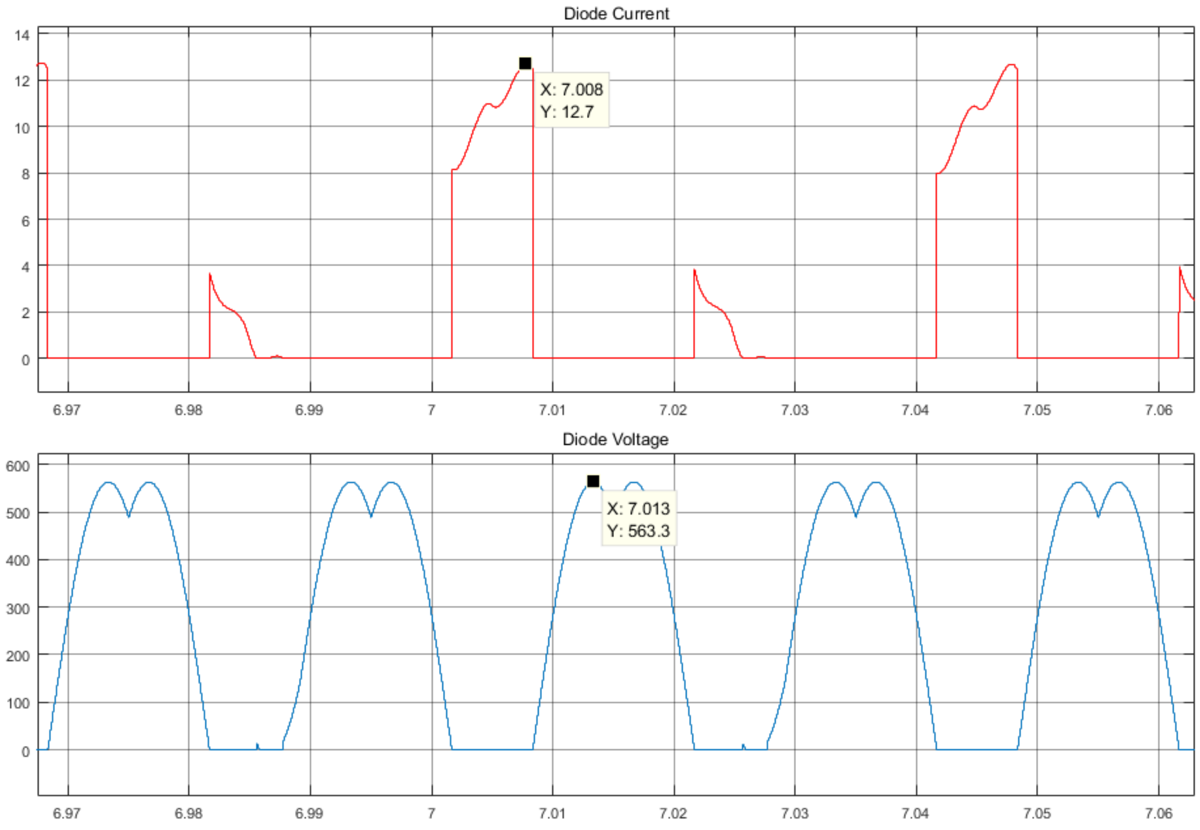

Figure 62: Rectifier Diode Voltage and Current Graph

For this voltage and current ratings, IXYS's DSI 35[3] rectifier diode product can be used. This is a rectifier diode with 800V forward voltage blocking capability and continuously 50A conduction capability. This diode complies with this application.

CONCLUSION

In this project a DC Motor application with all dimensions is investigated. Using Simulink© program, the DC Motor driver is modeled and it is driven by a rectified and filtered input voltage using a four quadrant chopper. Therefore, a unipolar PWM block is built and used in this project. The dynamic braking concept is studied and implemented also. Furthermore, current and speed controlling of a DC Motor is studied with different type of controllers. Consequently, device examples are suggested for this DC Motor driving application.

[3] (IXYS Corporation, 2000)

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