EE462 Spring 2016-2017
Project 2

DC Motor Drive and Full Bridge Topology

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Contents

1 Introduction

In that project , I tried to model a railway traction system. The system is consisted of 3 carriages , with a mass of 42 tons each and two motors driving each carriage .

Traction motors work like any other electric motor. Generally , in traction system DC motor with series field winding used because they are the oldest type of traction motors . However , in that project we will use PM DC motor with constant field current to simplify the project and focus on motor driver circuitry .

To obtain DC Motor driven via 4Q Chopper model , I used simPowerSystem library's blocks except control and signal units . I tried to use real power electronics components with their realistic characteristic to simulate a real behavior of the 4Q Chopper .

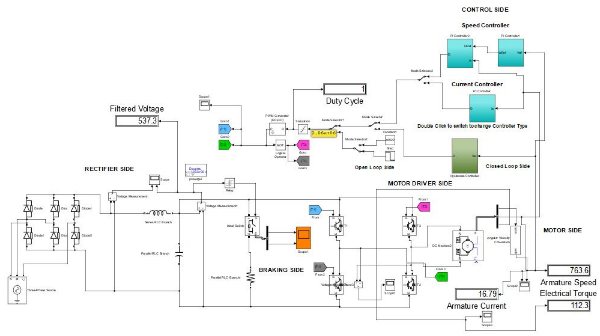

Figure 1: DC Motor and 4Q Chopper Simulink Model

The DC source of the DC machine obtained via rectified 3Θ AC voltage source . As a rectifier, I used 3Θ full bridge uncontrolled rectifier topology.The reason why I used that topology is to drive the motor I used 4Q chopper ,so I did not need any adjust option for rectifier.

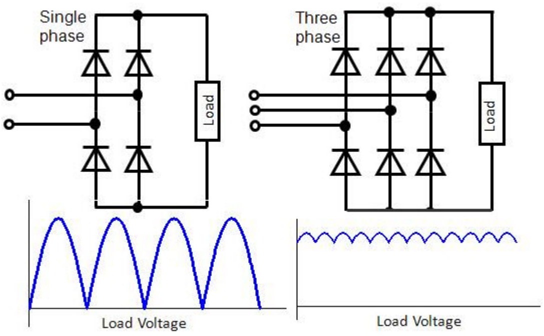

Figure 2: 1phase and 3phase Uncontrolled Diode Bridge Rectifier

In the beginning of the project , before combining everything I constructed the DC link filter individually . After some calculations , I could achieve the 1% ripple percentage . However when we combined with the motor side, the voltage ripple increased due to ripple on the motor side . The reason of the motor ripple is the nature of the DC machine . To clarify it is the ripple caused by mechanical torque. To overcome that problem I changed my values for L an C. Figure is taken from.

Lock Anti-Phase Drive topology used to drive the motor. In these topology , Q1-Q4 switched simultaneously ,and when they are off the reverse current flowed from the other switch's free wheeling diode. As a result , obtained terminal voltage is oscillating between Vin and - Vin .

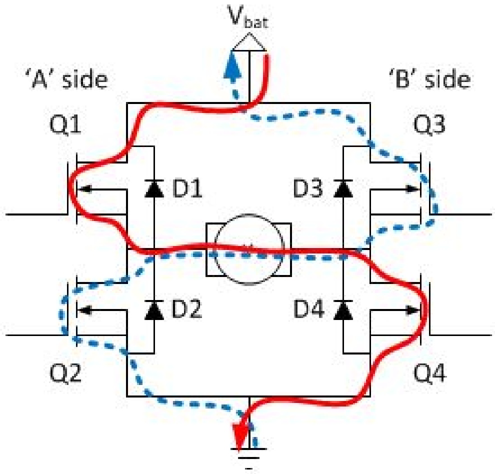

Figure 3: 1phase and 3phase Uncontrolled Diode Bridge Rectifier

2 Simulink Model

2.1 DC Motor Driver Part

2.1.1 Part A - Preliminary Design

Nowadays, AC power has much more low cost than DC power due to reproducing DC Power is much harder .Therefore a method for changing ac to dc is needed in relatively less expensive way as a source of dc power. In that project to convert AC to DC as i said before I used uncontrolled full bridge rectifier. However , due to nature of the converter there is too much undesirable ripple.To overcome that ripple I used a DC Link LC Filter.

The cut-off frequency of the filter and L and C values calculated as ,

$$w_0 = \frac{1}{\sqrt{L * C}} \tag{1}$$

After deciding certain capacitor range than I chose the inductor value with regards to equation 1. To simplify the system , I tried to calculate each component individually . For C and L values in mili level will be sufficient because we are working on 50 Hz and our priority is pass line freqeuncy and filter the others .

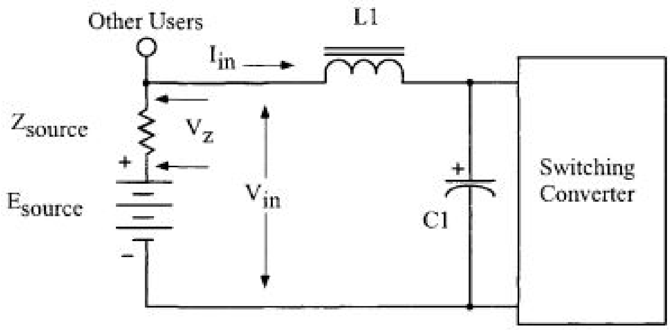

Figure 4: DC link LC filter topology

So if we consider the rectifier circuit is remote from DC machine ,

L = 1 mH , C = 5 mF is enough for now .
As you can see from **??** , the voltage ripple is lower than 1 % ripple .

To calculate switching frequency of the switches , I considered that the electrical time constant has to much more bigger than switching time so we can prevent to saturate the DC motor inductor.

$$t_e = \frac{L}{R} \tag{2}$$

After putting appropriate DC motor's inductor and resistor value to equation 2 , I find $t_e = 68ms$. So to satisfy $t_e >> t_s$ condition I chose $t_s \approx 125us$ or $f_s \approx 8kHz$

2.1.2 Part B - Modeling and Simulation

When we consider ,rectifier and DC machine driver constructed separately . Rectifier side circuit will be like ,

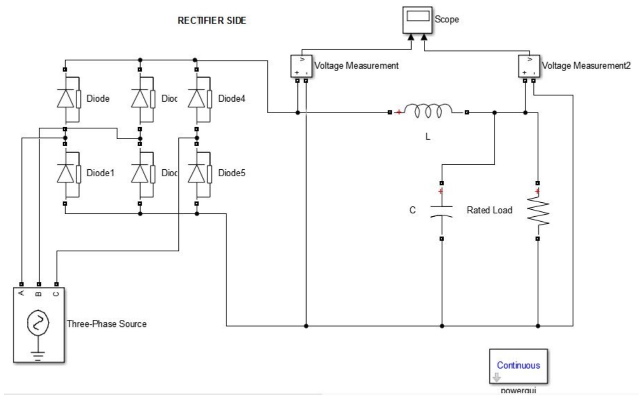

Figure 5: 3phase Diode Full Bridge Rectifier Simulink

Rectifier side ,for R = 0.95 Ω, waveforms will be like

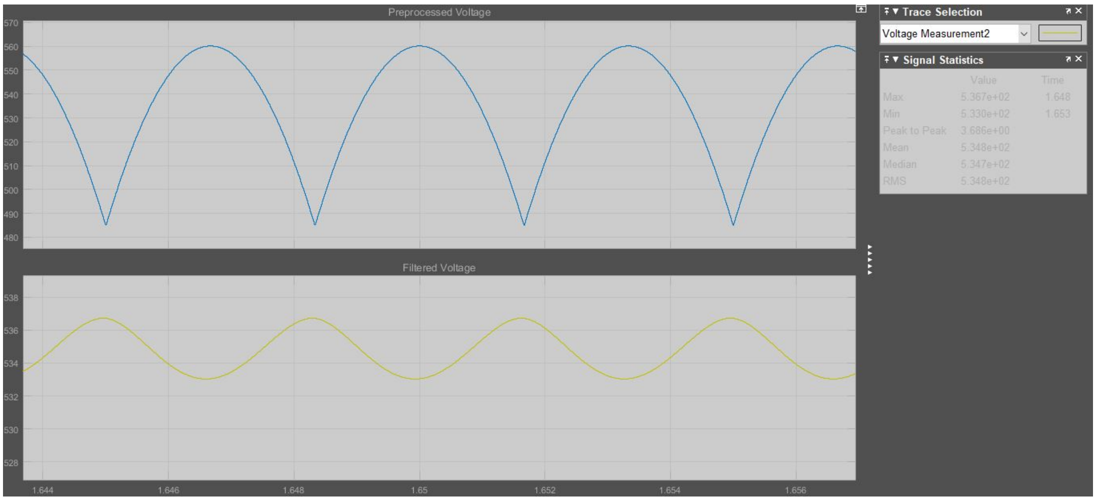

Figure 6: Preprocessed and Filtered Output Voltage when systems are Separated

We can obtain 4Q operation with four-quadrant full bridge chopper whether PWM is unipolar or bipolar . I chose bipolar PWM because we can obtain wider pulse widths than unipolar PWM .Bipolar PWMs, if the pulse width for one of the PWM states is too short, you can simply flip to the other PWM state, where the parallel signal will be correspondingly longer! So we are always guaranteed to have at least one interval within each PWM cycle (regardless of the duty-cycle value) where the parallel signal width is wide enough to easily facilitate an accurate reading of the motor current.However ,bipolar PWM fired full bridge chopper output voltage contains much more harmonic than unipolar PWM .

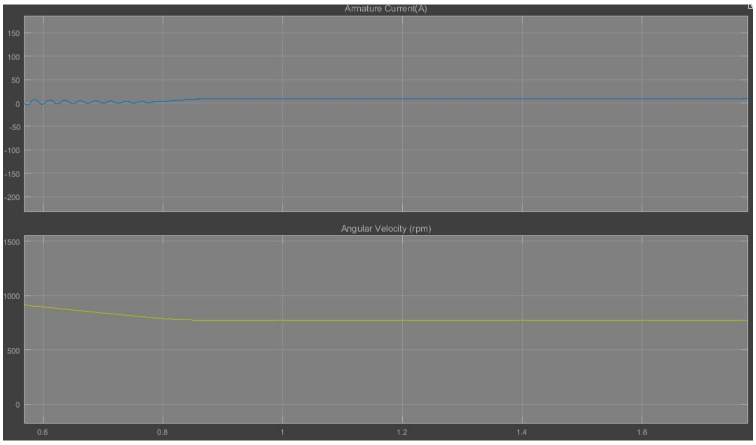

Figure 7: First Quadrant Current and Velocity same direction and positive

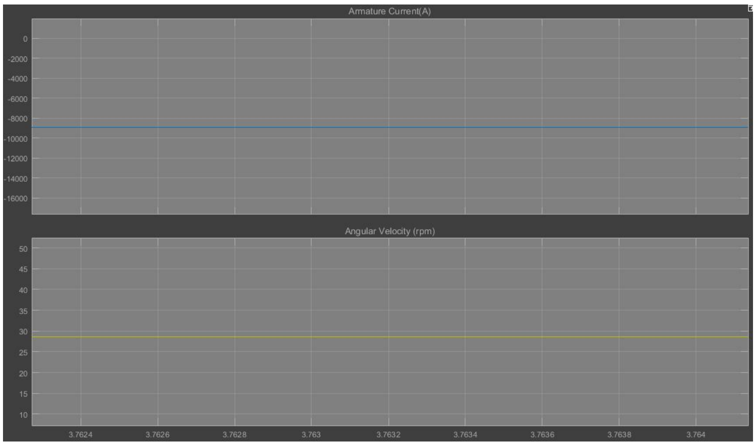

Figure 8: Second Quadrant Current and Velocity opposite direction and Velocity positive

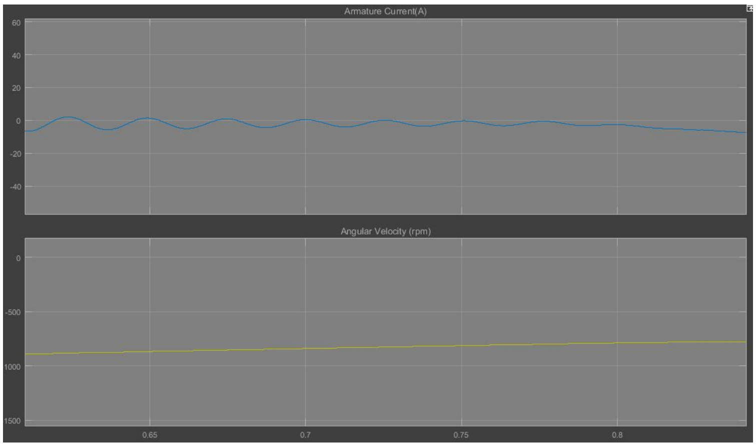

Figure 9: Third Quadrant Current and Velocity opposite direction and negative

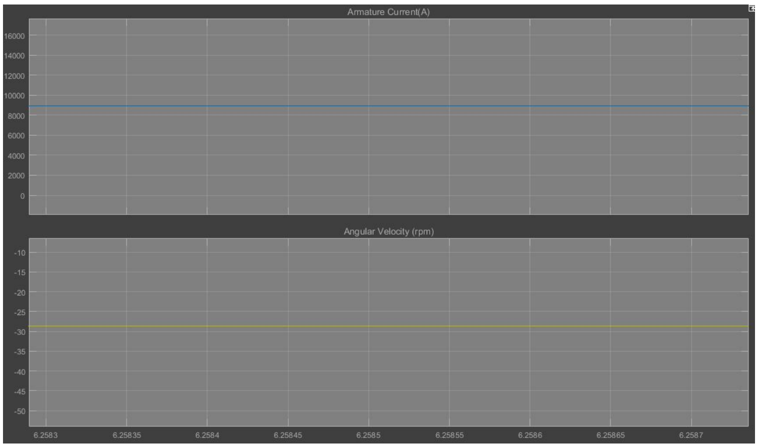

Figure 10: Fourth Quadrant Current and Velocity opposite direction and Current positive

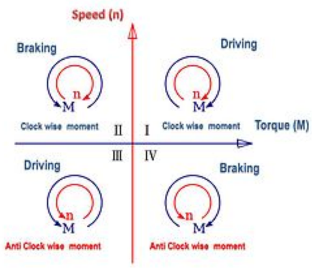

Figure 11: Four Quadrant waveform

DC Motor Driver side , for Vin = 540V

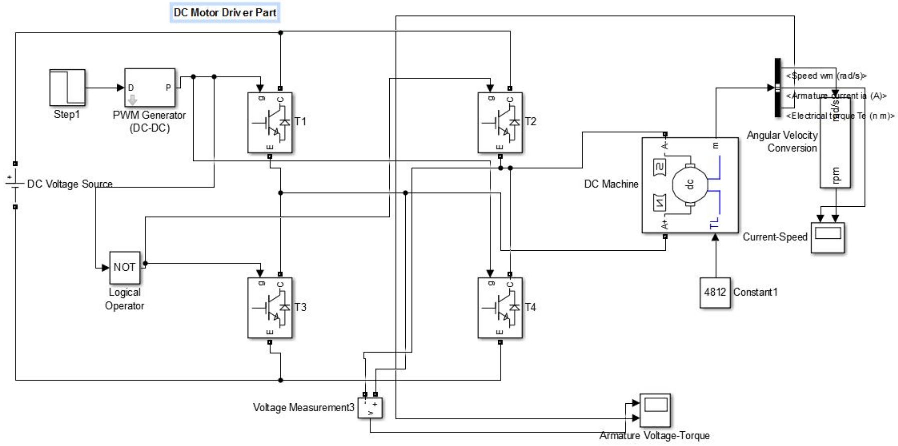

Figure 12: 4Q chopper and DC motor

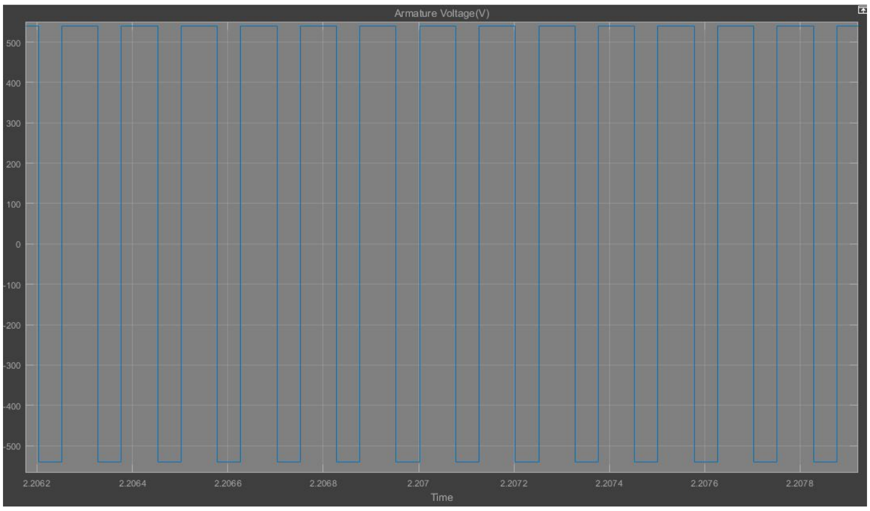

Figure 13: Armature Voltage when systems are Separated

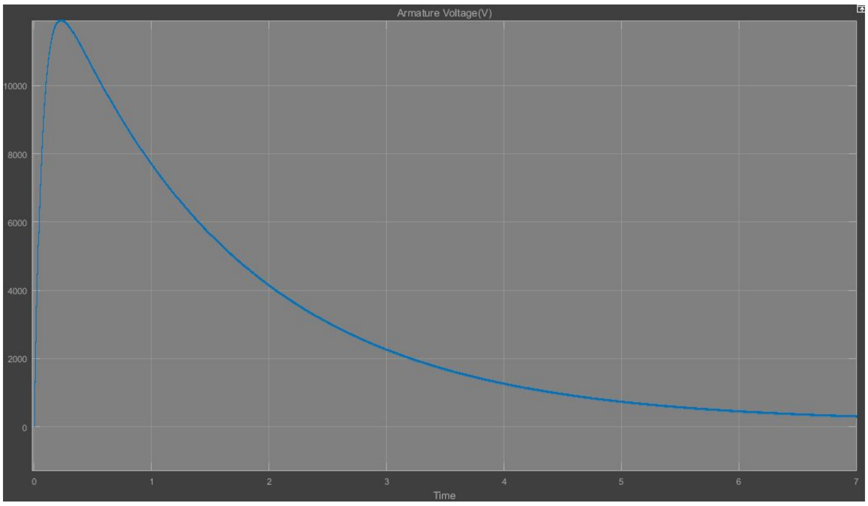

Figure 14: Electrical Torque Waveforms when systems are Separated

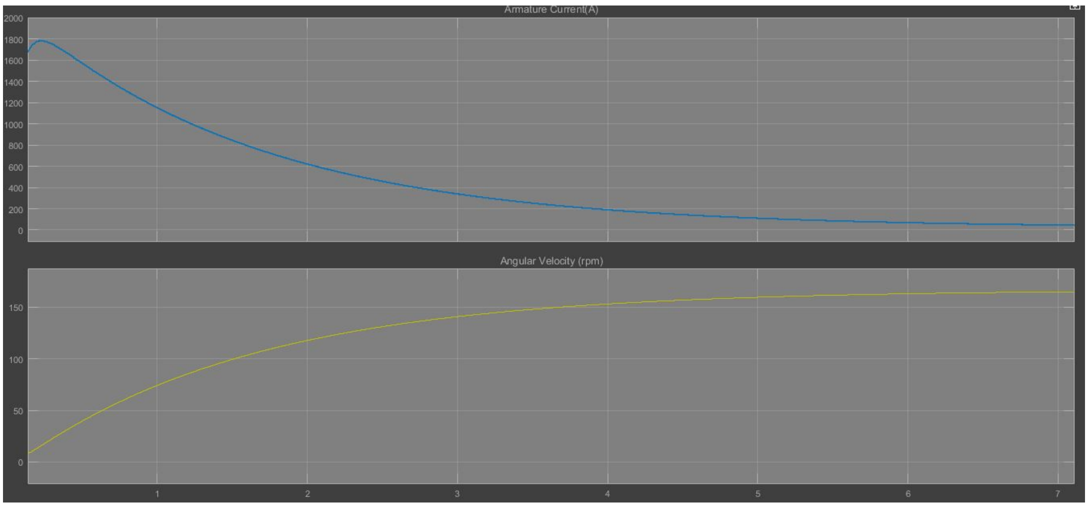

Figure 15: Armature Current and Motor Speed Waveforms when systems are Separated

When we combine both system,

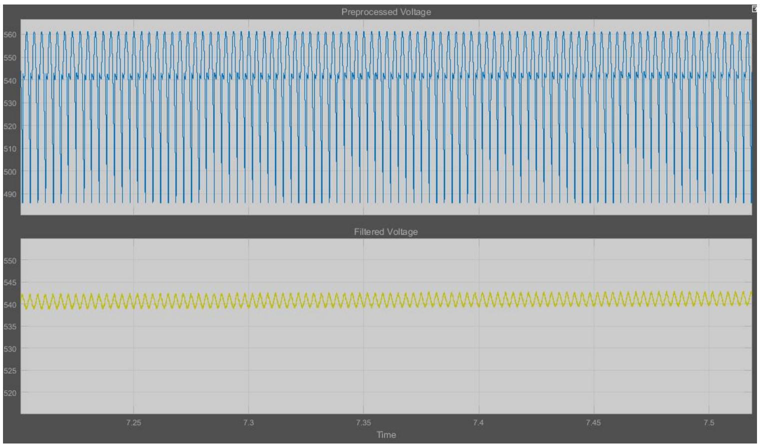

Figure 16: Preprocessed and Filtered Output Voltage when systems are together

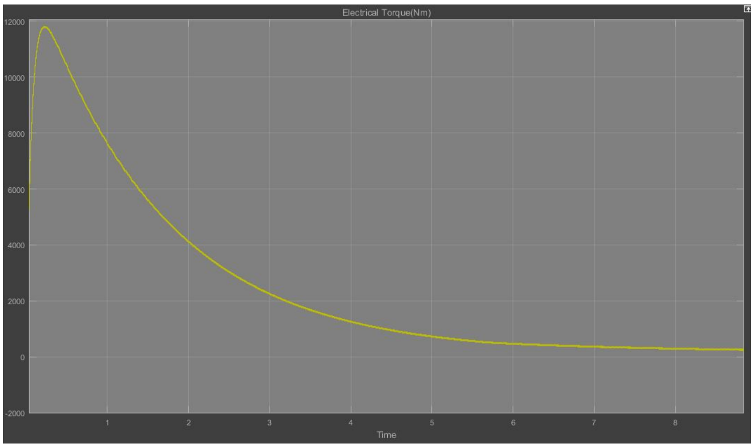

Figure 17: Electrical Torque Waveforms when systems are together

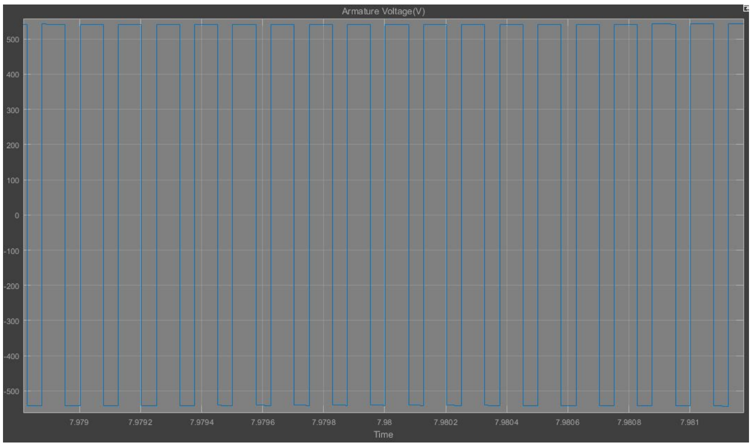

Figure 18: Armature Voltage Waveforms when systems are together

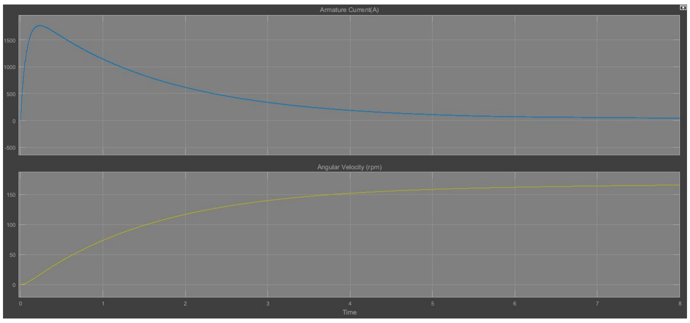

Figure 19: Armature Current and Motor Speed Waveforms when systems are together

After combining both of the system as I expected ,voltage peak-to-peak value increased so to decrease the voltage ripple I changed the inductor value with regards to equation 1 . The reason why the ripple increase after we combined both circuit is the effect of motor current ripple on the overall system. The source of the current ripple is the mechanical torque ripple due to nature of mechanical side of the motor. To decrease as I did we can change the filter capacitor and inductor value so the system will not be affected from the current ripple.

2.1.3 Part C - Open Loop Control

I derived the equations for Bipolar PWM method . In bipolar PWMs, one of the switch on state time is too short, the shunt signal will be correspondingly longer due to complementary switching between same legs switches. As a result , we are always guaranteed to have at least one interval within each PWM cycle (regardless of the duty-cycle value) where the shunt signal width is wide enough to easily facilitate an accurate reading of the motor current.That is the one of the most important advantages of the bipolar PWM . On the other hand , due to nature of the bipolar PWM there will be much more harmonics on output voltage . That is the one of the most crucial disadvantage of the bipolar PWM.

$$V_t = I_a * R_a + E_a \tag{3}$$

$$T_e = K_t * I_a \tag{4}$$

$$E_a = K_e * w \tag{5}$$

First one , if we combine equations 3 - 5

$$V_t = \frac{T_e * R_a + K_e * w * K_t}{K_t} \tag{6}$$

Voltage Transfer Ratio equation of the 4Q chopper topology,

$$V_t = (2 * d - 1) * V_i \tag{7}$$

In our case , load torque is equal to zero because we are moving on horizontal direction and there is not any torque due to weight of the carriages. So our electrical torque in steady-state is ,

$$T_e = T_f \tag{8}$$

If we combine equations , 6 - 7

$$w = \frac{(2 * d - 1) * V_i * K_t - T_e * R_a}{K_e * K_t} \tag{9}$$

Than converter 9 to ,

$$d = \frac{\frac{T_e * R_a + K_e^2 * w}{K_e * V_i} + 1}{2} \tag{10}$$

and V_t calculated from above equation for rated values

To calculate the duty cycle of the system when it is in its rated speed, we can use equation 10 . So , when system is turning its rated speed d = 0.8922 ,

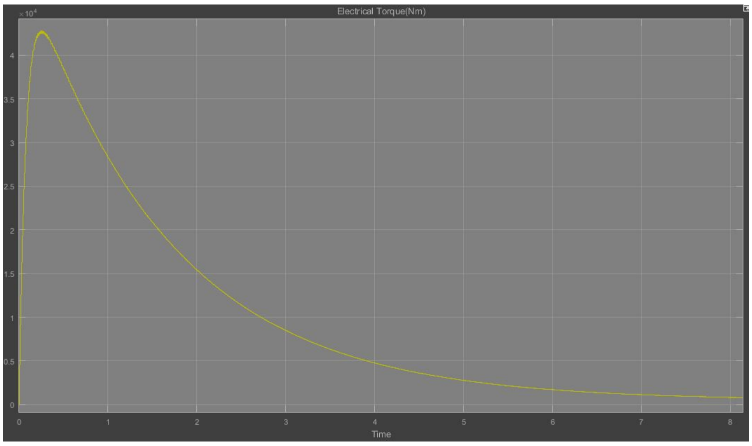

Figure 20: Electrical Torque Waveforms when systems are together at full rated speed

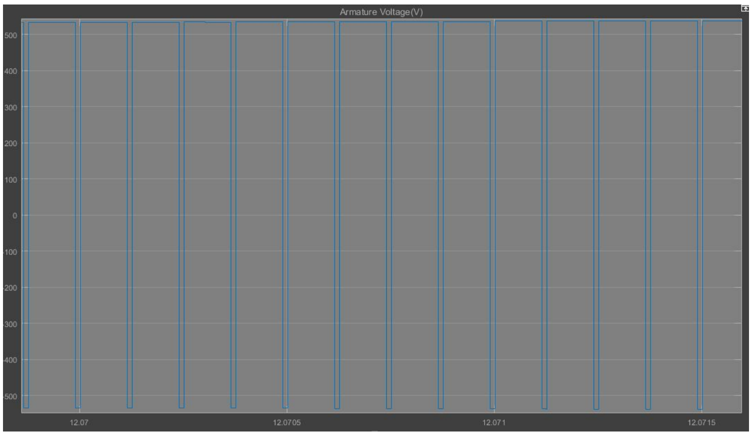

Figure 21: Armature Voltage Waveforms when systems are together at full rated speed

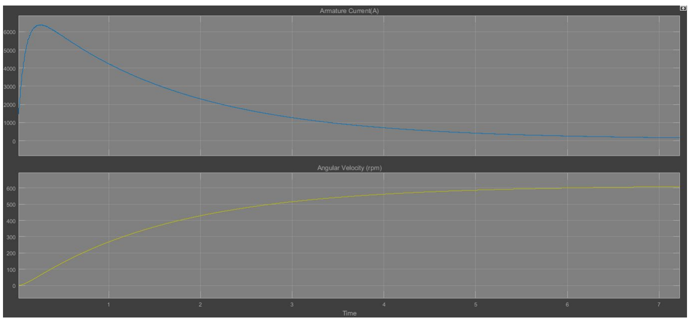

Figure 22: Armature Current and Motor Speed Waveforms when systems are together at full rated speed

When system is working on half rated speed the duty cycle will be d=0.6961 and waveforms will be ,

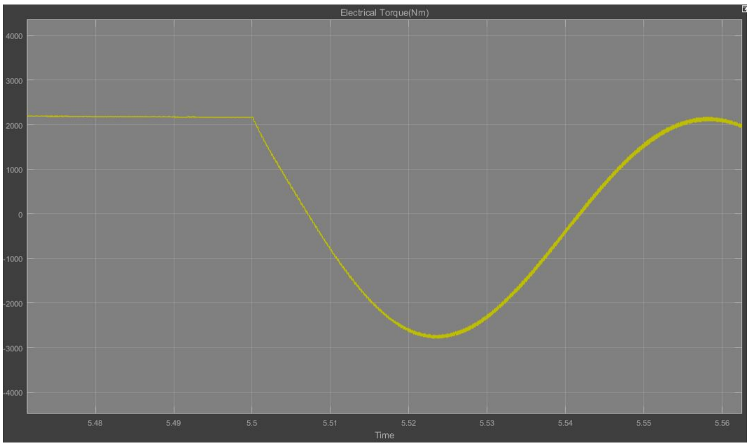

Figure 23: Electrical Torque Waveforms when systems are together at half rated speed

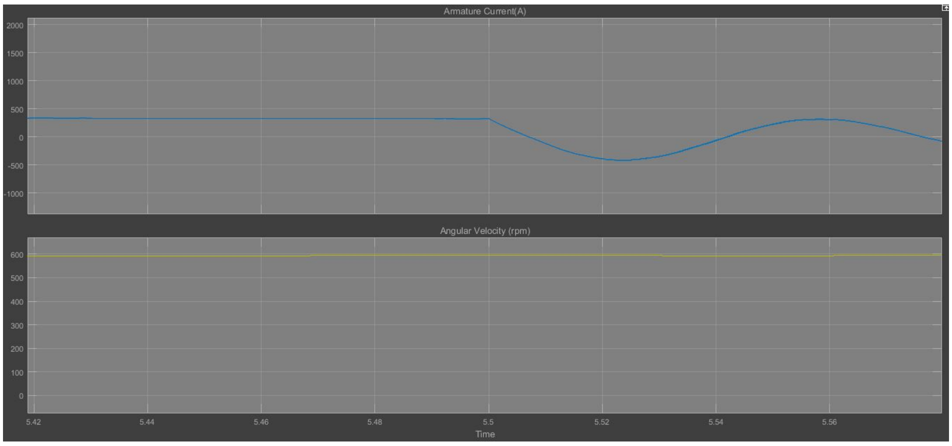

Figure 24: Armature Current and Motor Speed Waveforms when systems are together at half rated speed

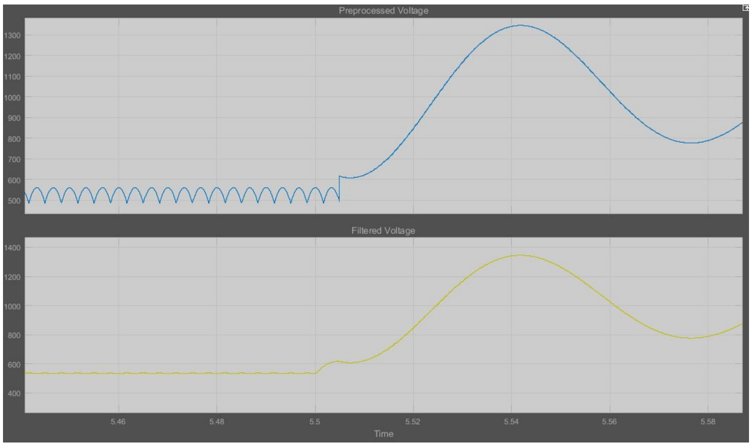

Figure 25: Filtered Output Voltage (DC Link Voltage) at half speed

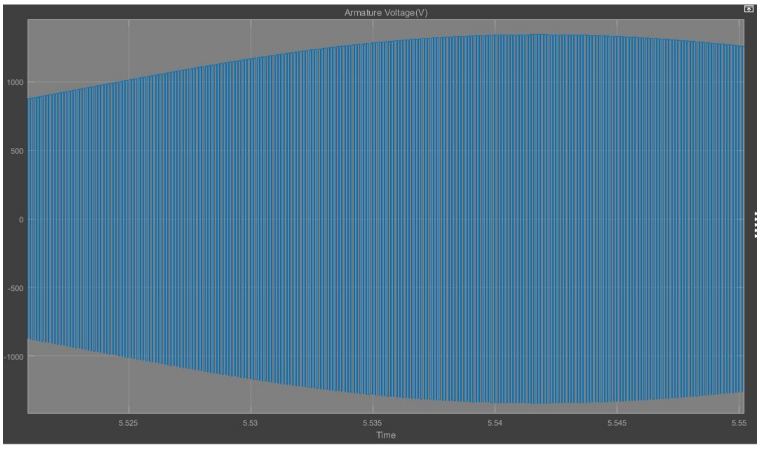

Figure 26: Armature Voltage Waveforms when systems are together at half rated speed

Normally ,when duty cycle is constant the system will turn with regards to duty cycle value . If duty cycle is bigger than 0.5 in motoring mode, and generating mode in opposite case . However, when we change duty cycle while motor is rotating to decrease the speed to apply negative torque motor current will decrease below the zero . So the motor will enter to braking mode or regenerative braking. As we can see from above the figures, there is stress on DC Voltage link while we are on regenerative braking mode .To decrease that stress , resistance or chopper can be used .

2.1.4 Part D - Dynamic Braking

When we add transition delay our voltage peak will decrease because if we try to brake the motor in very short time there will be a huge current to bring the mechanical energy to desired value .

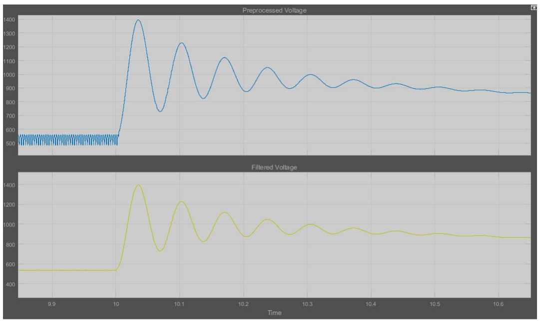

Figure 27: Braking State for a long Time

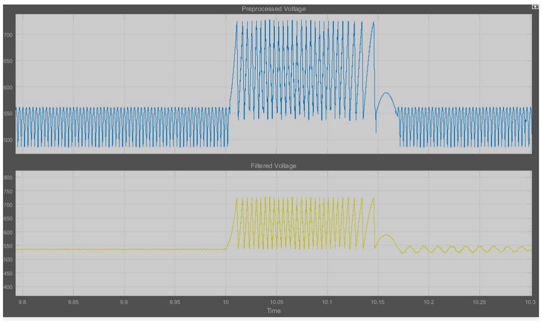

Figure 28: DC Link Filter Voltage when Braking State with Dynamic Braking Resistance

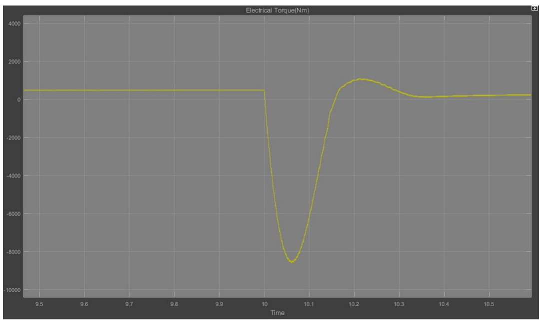

Figure 29: Torque waveforms when Braking State with Dynamic Braking Resistance

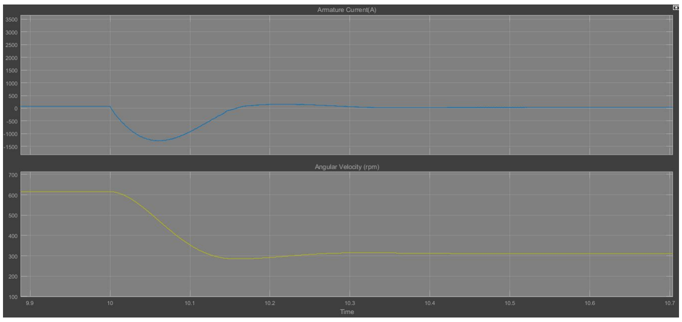

Figure 30: Armature Speed and Armature Current when Braking State with Dynamic Braking Resistance

I chose the resistance value with regards to this webpage `http://www.frizlen.com/en/service/braking-resistor-calculator/?no_cache=1` . To calculate the braking energy , I used the kinetic energy loss on the system.

$$E_k = \frac{J_t * ((V_i)^2 - (V_f)^2)}{2} \tag{11}$$

Where V_i is initial velocity in our case 600 rpm , and V_f is the final velocity in our case its value is 300 rpm . Plus, J_t is 1240 $kg * m^2$.

As we see from figure 31 , our current ratings will be maximum 980A and voltage will be 725 V ,and I chose the resistance value 0.75 ω

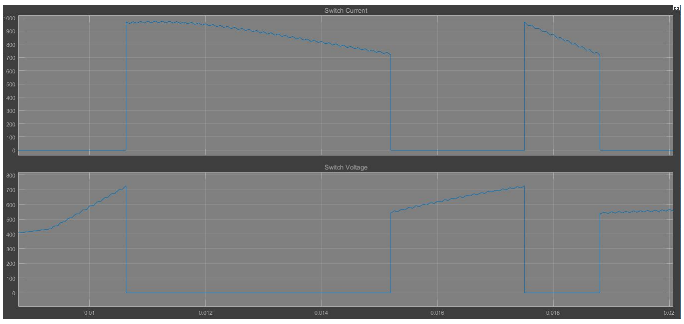

Figure 31: Dynamic Braking Switch Voltage and Current

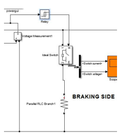

Figure 32: DC Machine with Dynamic braking Resistance

2.1.5 Part E - Closed Loop Control

PID Controller

A PID controller continuously calculate the error and with regard to difference between a desired value , applies a correction based on proportional, integral, and derivative terms (P,I,D respectively). Proportional mean current time errors, Integration corresponds to past time errors, Derivative corresponds to future time errors in other words error memory.

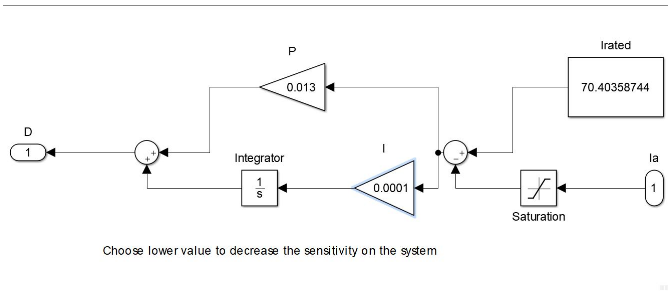

Figure 33: PID Controller

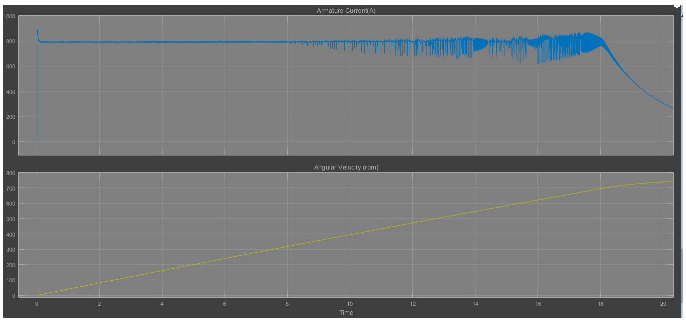

Figure 34: Armature Speed and Armature Current waveforms when system has PI Controller

To have non-susceptible system , I tried to chose lower P and I value because if we chose P as 1 or above the system will affect too much even there is small errors. Plus, I chose Integration value by using trial and error method .

Hysteresis Controller

A bang–bang controller (on–off controller), also known as a hysteresis controller, is a controller that switches between two different states .They are often used to control a plant that accepts a binary input,such as PWM controlled DC Motor as our project . Most known bang-bang controllers(hysteresis controller) are residential thermostats. Due to the discontinuous control signal, systems these include bang–bang controllers are variable structure systems, and bang–bang controllers are thus variable structure controllers.

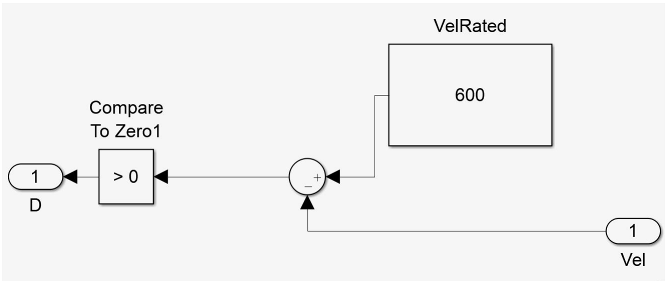

Figure 35: Hysteresis Controller

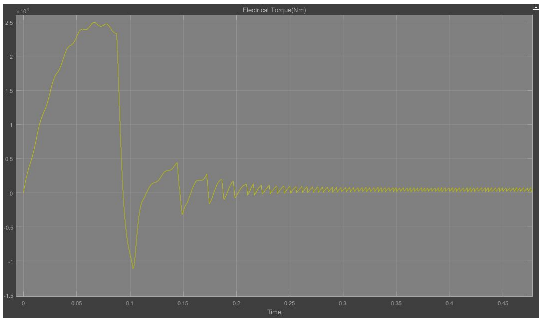

Figure 36: Electrical Torque waveforms when system has Hysteresis Controller

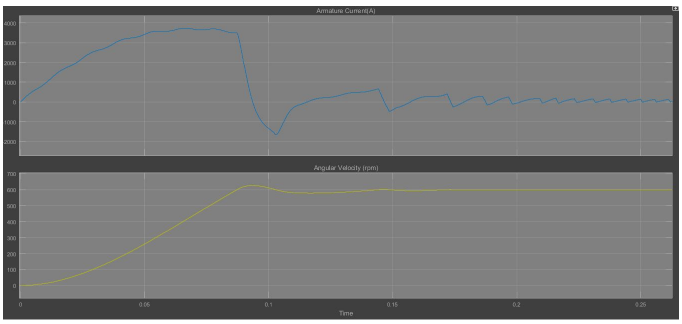

Figure 37: Armature Speed and Armature Current waveforms when system has Hysteresis Controller

Most of the control systems has some properties such as steady-state error, overshoot and transient response . If we compare Hysteresis and PID controller , from the viewpoint of controlling these properties PID is better than Hysteresis controller because PID basically is predictive and tries to minimize the time it takes to get to rated values. Also , hysteresis controller has too much ripple or harmonics on current due to discrete control method. However , in terms of system robustness PID has too much on and off state so the Hysteresis Controller will endanger less the switches in real case .

2.1.6 Part F - Speed Controller

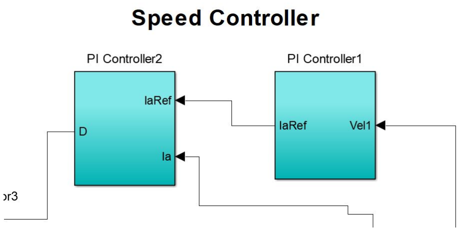

Figure 38: Speed Controller Circuit Diagram

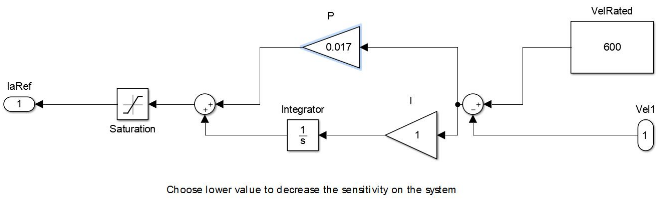

Figure 39: Speed Controller Part 1 - Speed PID

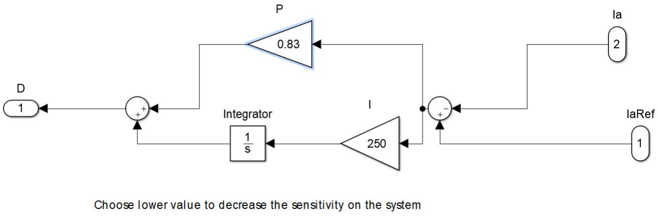

Figure 40: Speed Controller Part 2 - Current PID

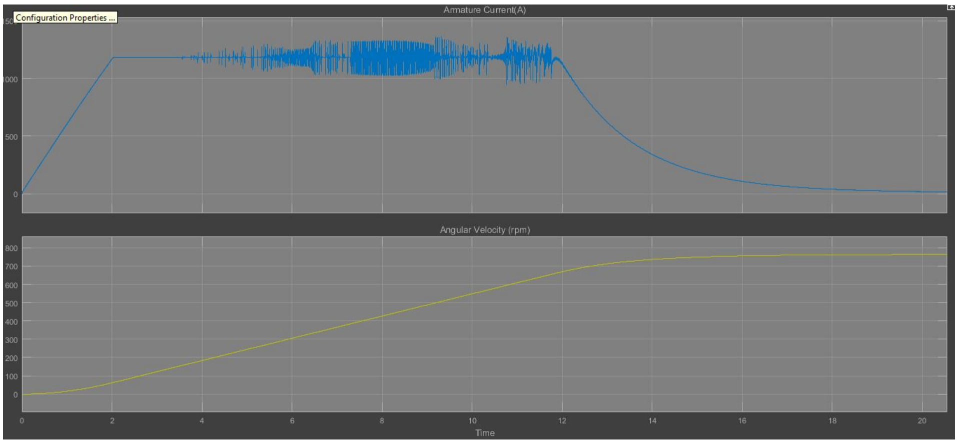

Figure 41: Armature Current and Armature Speed Waveform when system has Speed Controller

As we see from Part-E if we use only current controller ,we can not limit our acceleration and we do not have fully control on the system . By combining both controller and tune the PI values well we can achieve a soft moving train so more comfortable motion for passengers or sensitive carload.

2.1.7 Part G - Device Selection

In this project , diode for rectification , IGBT with free wheeling diode for motor driving used as a semiconductor devices. As I tried to explain before , I did not used fully controlled rectifier topology because I have two series control circuit and I can adjust motor armature voltage via full bridge topology. Plus , diode ratings are ,

V_r = 325*1.5 V multiplication with 1.5 due to reverse recovery phenomena ,
I_r = 265*1.5 A

With regards to ratings I chose ,
`https://www.semikron.com/dl/service-support/downloads/download/semikron-datasheet-skd-100-07187`
as a diode rectifier.

IGBT with anti-parallel diode or IGBT with free wheeling diode commonly used in DC Motor driver circuitry . When we do not have to switch our circuitry with high frequency by using IGBT we can use both advantages of BJT and MOSFET . Also , I do not need to use SiC or GaN technology because my switching frequency is small .As a result , I can decrease the cost by using Si technology. With regards to ratings I chose ,

V_r = 270*1.5 V multiplication with 1.5 due to Peak Voltage and stress margin
I_r = 75*1.5 A

`http://ixapps.ixys.com/DataSheet/MKI75-06A7_MKI75-06A7T.pdf`

2.1.8 Load Inertia Calculation

To calculate load inertia ,firstly we have to find our radius. To calculate the radius,

$$54\frac{km}{h} = \frac{54 * 1000}{3600} = 15\frac{m}{s} \tag{12}$$

$$15\frac{m}{s} = 2 * pi * R * (RPS) \tag{13}$$

Where RPS is revolution per second and its value can be calculated easily by dividing 60 the 600 RPM .

$$R = \frac{15}{2 * pi * 10} \tag{14}$$

So the R value will be , 0.239 m

$$J = M * R^2 \tag{15}$$

In our case M is equal to 21.000 kg .As a result , the J value will be 1196.9 $kg * m^2$

2.2 Conclusion

In this project , I tried to understand and analyze Full Bridge driven DC Motor . I mainly focused on ,

- Four quadrant operation for full bridge
- The affects of DC Motor to source side
- Control method for DC Motor
- DC link filter to prevent DC Motor ripple to source side
- The benefits of Dynamic Braking Resistance to source side

I used the bipolar switching topology to change the direction of the motor easily only by changing duty cycle. To show the full bridge is able to work as four quadrant , I added very huge load torque for show the generative working quadrant . By using huge load torque, I tried to simulate the train moving while train is going uphill or downhill .

After combining all the systems , I saw that there is some dangerous ripple on the source side. So to eliminate them I changed filter capacitance and inductance value. This change decreased the ripple but increased the cost. However ,to obtain safe operation for the system that was inevitable.

By applying different control topology , I saw the difference between PID and Hysteresis controller topology. In huge DC motor systems such as railway locomotion we have to have control on the whole system so the PID will be much more appropriate for our project because hysteresis control has less stress on switching devices but gives us less control on the system . Furthermore, by combining two or more controller we can increase the controllability of the system . As a result , I combined current and speed controller so I achieve the acceleration control even if just a pinch .

To prevent the dangerous increase on the dc link voltage while motor is braking , I used dynamic braking resistance . When current changed the direction of the flow, the current can go through resistance instead of going through dc link capacitor . So , the dangerous voltage stress on capacitor will be eliminated.

To sum up, by using appropriate control method we can keep our system in safe operation area, so we can achieve our mission perfectly. To have safe drive while we are using a traing, we have to use appropriate and well developed algorithms with very good MCU,and has overall control on the system.

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