EE462 Spring 2016-2017
Project 3

3Θ Induction Motor Drive and Analysis

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Contents

1 Introduction

The 3Θ induction motor was invented by Nicola Tesla in and around the late 1880's as well as others. Its main feature is that it is able to create a rotating magnetic field through the application of 3Θ alternating currents having a phase difference of 120 degrees. When applied to the stator these induce a rotating magnetic field on the rotor which interacts with that produced by the stator to produce an electromagnetic torque in the air gap.

Tesla discovered that by using a 120 degree phase difference in the 3Θ supply and by also physically placing the windings 120 degrees apart that he could produce a rotating magnetic field which enabled the motor to be self-starting.

As all electric machines 3Θ induction motor also consisted of stator and rotor. Stator of 3Θ induction motor is made up of numbers of slots to construct a 3Θ winding circuit which is connected to 3Θ AC source . As it said before , 3Θ winding are adjusted in such a way in the slots that they produce a rotating magnetic field after 3Θ . Rotor of 3Θ induction motor consisted of cylindrical laminated core with parallel slots that can carry conductors. Most of the time conductors are heavy copper or aluminum bars which puts in each slots and via the end rings they short circuited. To decrease the effect of the harmonics on rotating MMF ,the slots are skewed a little . From figure 1-2 you can see circuit diagram and cut view of the 3Θ induction motor respectively,

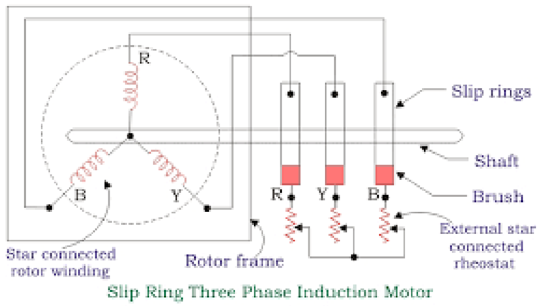


Figure 1: The circuit diagram of 3Θ Induction Motor

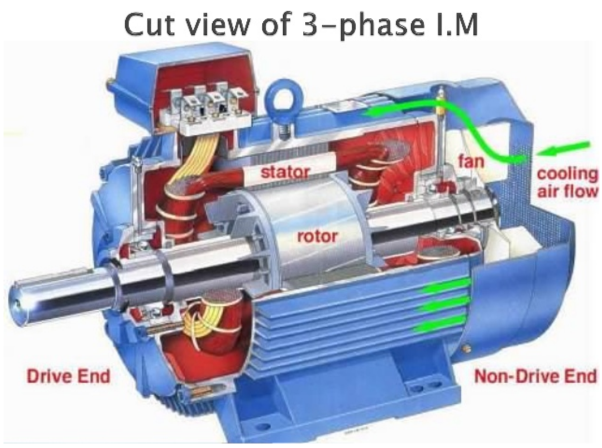


Figure 2: The cut view of 3Θ Induction Motor

In this project ,our purpose is analyzing 3Θ induction motor driver load and input side.

2 Part A

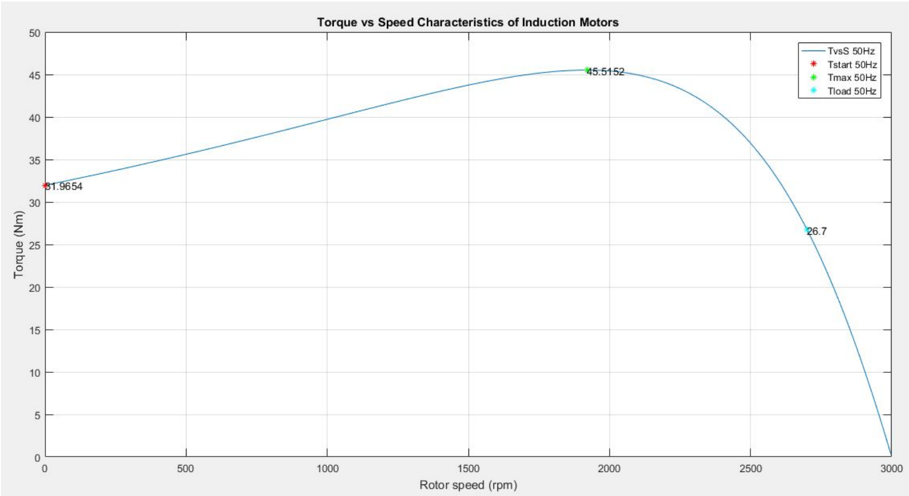


Figure 3: Torque vs Speed Characteristics for rated Frequency and Voltage

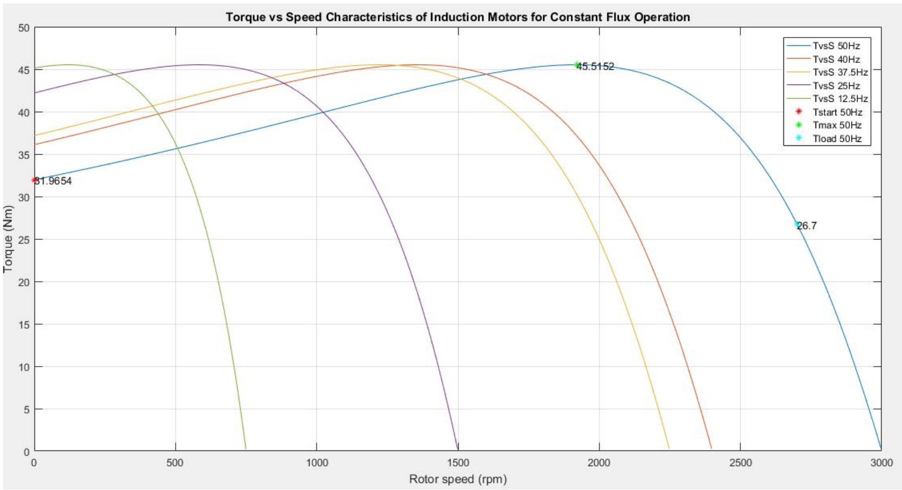


Figure 4: Torque vs Speed Characteristics for different V and f value ($\frac{V}{f}$ constant)

In figure 3 , I tried to show the Torque-speed characteristic of the induction motor . To find the characteristic firstly I found the thevenin equivalent of the induction motor,than find the speed torque relation from the equivalent circuit.Than I used equation 1 to draw the waveform ,

$$T_e = \frac{3(V_{th})^2 * r_2'}{((R_{th} + \frac{r_2'}{s})^2 + (X_{th} + X_2)^2)s * (w_s)} \tag{1}$$

When we change the frequency ,our synchronous speed decreased and our waveform shifted to zero side according to frequency value. Our thevenin resistance is too much ,so the loss is coming significant . To solve this problem,I wrote a code which try to boost voltage and voltage boost amount decided according to frequency value.As a result,each frequency maximum torque value stayed same.

To calculate the maximum torque ,I found the slip when $\frac{r_2*(1-s)}{s}$ has maximum power on it. Slip was,

$$s_{maxT} = \frac{r_2'}{\sqrt{R_{th}^2 + (X_{th} + X_2')^2}} \tag{2}$$

When I put this found slip value , in equation 1 and maximum torque or pull out torque equation,

$$T_{max} = 3\frac{0.5V_{th}^2}{\omega_s}\frac{1}{(R_{th} + \sqrt{R_{th}^2 + (X_{th} + X_2')^2}} \tag{3}$$

To find the starting torque, I put zero value for slip in equation 1 and I calculated it. To calculated results are on figure 3.

3 Part B

3.1 Power Stages

In the project ,there is several power stages to drive an induction motor . These stages are,

- First stage is rectifier part in which we try to convert AC to DC
- Second stage is DC-Link Filter part in which we try to reduce the effect of rectifier harmonics on the motor side
- Third stage is Chopper resistance part in which we try to drive the system for four quadrant operation
- Fourth stage is the inverter part in which we try to convert DC to AC .Also , via controlling frequency and voltage we can also control induction motor speed

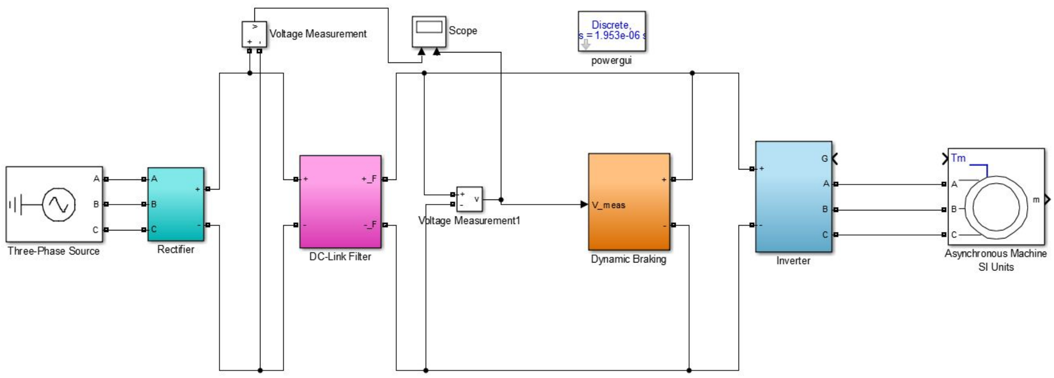


Figure 5: Overall power stages of the System

3.1.1 Rectifier Part

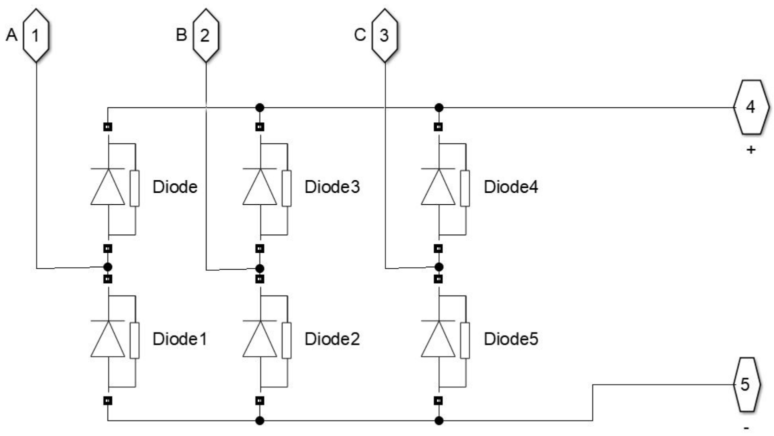


Figure 6: Uncontrolled 3Θ Rectifier

I preferred uncontrolled 3Θ rectifier to convert AC to DC converter because I will control Induction Motor speed by changing inverter sinusoidal reference amplitude and frequency.

3.1.2 DC-Link Filter Part

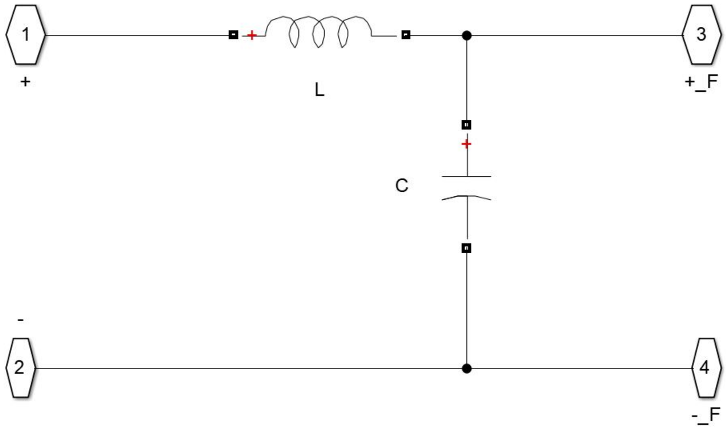


Figure 7: DC-Link Filter

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

$$w_0 = \frac{1}{\sqrt{L * C}} \tag{4}$$

After deciding certain capacitor range than I chose the inductor value with regards to equation 4. 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 frequency and filter the others . So I chose the C = 15e-3 F and L = 1e-3 H .

3.1.3 Chopper Part(Dynamic Braking Resistance)

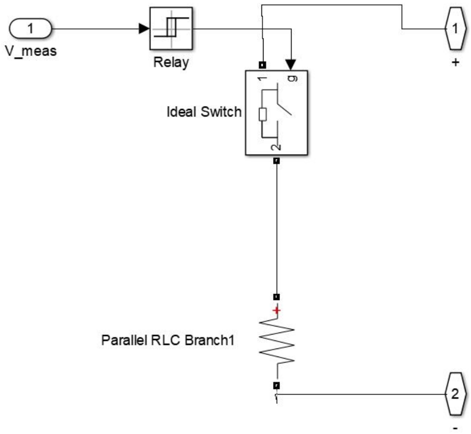


Figure 8: Dynamic Braking Resistance

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.

$$E_k = \frac{J_t * ((w_i)^2 - (w_f)^2)}{2} \tag{5}$$

Where w_i is initial velocity in our case 600 rpm , and w_f is the final velocity in our case I will calculated it with regards to speed regulation which calculated in Part D)(Closed loop Control)

3.1.4 Inverter Part

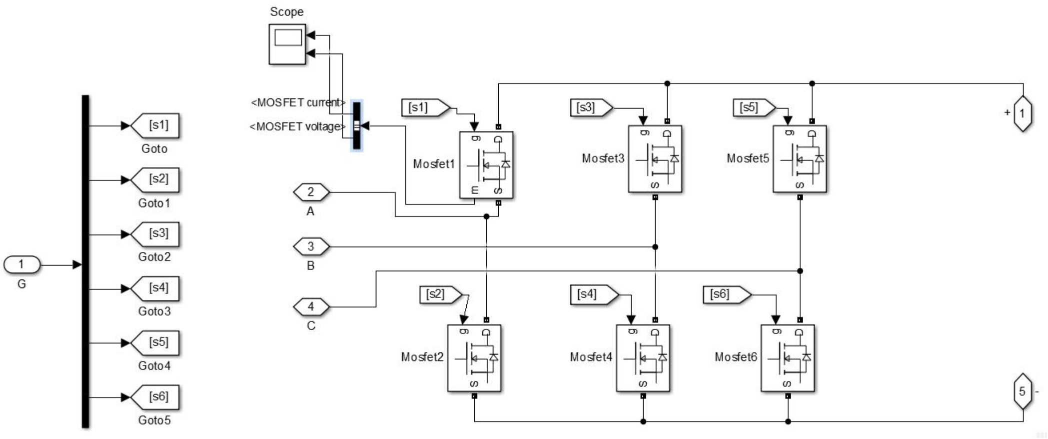


Figure 9: 3Θ Inverter

In this part I tried to explain to you the structure of the inverter and PWM method I used.Also, I wanted to explain what is SVPWM and how it works.

In figure 9,one can see that I used 3Θ IGBT based Full Bridge Inverter.The purpose of the inverter is , converting DC voltage to 3Θ AC voltages.The input voltage, output voltage and frequency, and overall power handling depend on the design of the specific device or circuitry. The inverter does not produce any power; the power is provided by the DC source.In the beginning of the project I started with MOSFET because the voltage level was not high and the system high frequency. However,to satisfy motor rated voltage I increased the grid line to line voltage level from 400 to 690 .So the dc link voltage increased from 540 to 960 according to $\frac{3}{\pi}\sqrt{2}V_{ll_{rms}}$. After I changed the grid voltage ,to construct more robust inverter , I changed my semiconductor and I used IGBT instead of MOSFET. In an Inverter , there is two important property.The first important property is M_a which is modulation index (equation 7),and the second important property is M_f which is modulation index (equation 8) . By changing these properties ,we can adjust our output voltage value. If I used SPWM(Sinusoidal PWM) and we work on linear region , our output voltage input voltage relation is ,

$$V_{ll_{rms}} = \frac{\sqrt{3}M_a V_d}{2\sqrt{2}} \tag{6}$$

In equation 6 , one can see that we can never obtain V_{dc} . Also , SPWM harmaonic quality is not well and not sufficient .To overcome these problems and to learn another concept I used SVPWM(Space Vector Pulse Width Modulation) because we can obtain closer value to V_{dc} by SVPWM and our harmonic content is much more better .

$$M_a = \frac{V_{cont}}{V_{tri}} \tag{7}$$

$$M_f = \frac{f_{tri}}{f_{cont}} \tag{8}$$

SVPWM differ than SPWM(Sinusoidal PWM) by special way of determining the switching sequence of upper semiconductor switches of a 3Θ VSI. SPWM try to determine the switching frequency with regards to $\frac{2*\pi}{3}$ phase difference between three legs . However, SVPWM try to convert three dimension 3Θ frame to two dimension α-β frame (equation 10), than try to find output voltage vector with regards to figure 10 and equations 9-11.As a result , by calculating these equations SVPWM can be used even in embedded systems. [5]

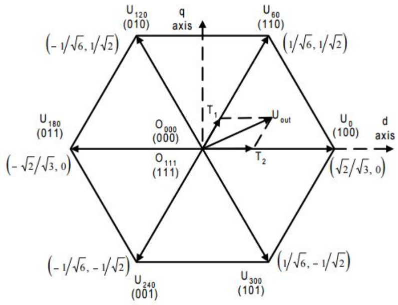


Figure 10: Space Vectors

As we see from figure 10 , to find U_{out} , we have to some basic vector calculus . To find output vector ,

$$\frac{1}{T} * \int_{(n+1)*t}^{n*t} U_{out}(t)dt = \frac{t_1 * U_x + t_2 * U_{x+60}}{t} \tag{9}$$

To convert three dimension to two dimension ,

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} * V_{dc} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{10}$$

One of the PWM cycle period is consisted of $t_1 + t_2$ if their sum is equal to period . If their sum is smaller than period in other words when U_x or U_{x+60} vectors not used system is in rest state or basically we can say currently used space vectors are U_{000} or U_{111} . So we can generalize t_1 or t_2 ,

$$t_{pwm} * U_{out} = t_1 * U_x + t_2 * U_{x+60} + t_0 * (0_{000} \,||\, 0_{111}) \tag{11}$$

To generalize the t_1 or t_2 calculation and to not depend on to sector selection , most of the application use matrix demonstration of the equation 11 and for each sector they calculate the matrix value and create a look up table to use this values while doing the computations. To sum up , only by considering magnitude and phase of the output vector they try to drive the inverter. For example, MatLab SVPWM use this method to obtain desired semiconductor switches gate signals.

In the project to obtain SVPWM , I used MatLab SVPWM (figure 11) block in internally generate mode while I was in open loop control. So only by deciding switching frequency,desired waveform frequency and modulation index , I obtained desired semiconductor switches gate signals.

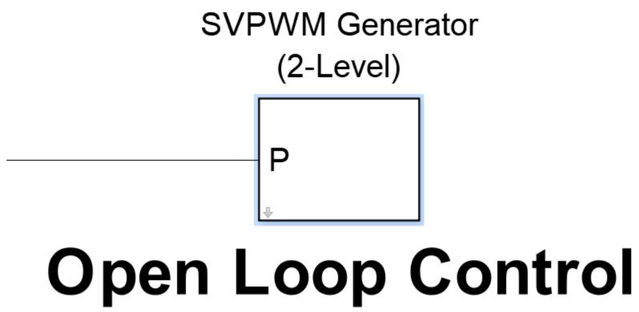


Figure 11: Space Vector Pulse Width Modulation(SVPWM) Block

3.2 Sensors & Control and Components

Controlling a 3Θ induction motor speed is one of the most important objectives of the project. So as a control variables I used Voltage and frequency. Before explaining how I will control these variables , I have to explain why I chose these variables. The torque of the induction motor depends on the voltage and the frequency of the motor . So by changing these values , I can generate the required torque,as a result required speed. Also , to achieve constant flux operation I have to keep the ration between voltage and frequency constant. So, if I control these variables from same controller ,I can handle constant flux operation.

Dynamic braking resistance is working when the dc link voltage exceed certain values. So I have to measure the DC link voltage . To obtain the voltage I measured the voltage value after the dc link filter via Isolation Amplifier based measurement circuit . Measurement circuit is approximately like ,

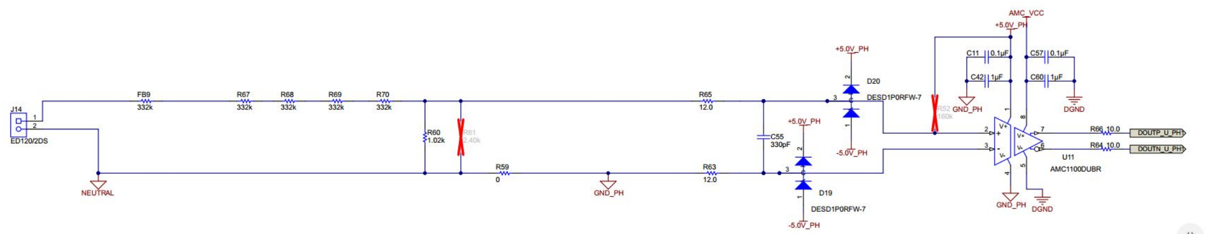


Figure 12: Voltage Measurement via AMC1100 Isolation Amplifier

In figure 12,one can see that the circuit try to convert the dc link voltage to ADC level voltage signal (0-3.3V) ,so the DSP can measured it.This operation may decrease system accuracy ,but it will simplify the system.Also, it will prevent the system exceed rated values .

To obtain frequency and voltage I used scalar speed controller combined with Space Vector Modulator.So I measured rotor speed of the induction motor via an optical encoder. To explain the controller in better way ,I explained the algorithm step by step,

- To calculate the speed error of the system I subtracted actual rotor speed from reference or desired rotor speed
- To decrease the error , I applied adaptive PID controller,so I obtained slip speed of the induction motor and by adding this value with actual rotor speed , I calculated the desired synchronous speed
- I divided the synchronous speed to $\frac{poleNumber}{60}$,so I obtained frequency value
- The voltage is calculated according to current frequency.
  - Multiply the frequency with a constant which is $\frac{400}{50}$,so find the base voltage value
  - Calculate the voltage boost amount according to frequency via BoostVoltageCalculator Algorithm (Appendix A) than add to base voltage value.So the motor stayed in constant torque region
- As a result, obtained frequency and voltage magnitude are the sinusoidal reference voltage amplitude and frequency ,in other words by changing modulation frequency and modulation index I tried to change induction motor speed.

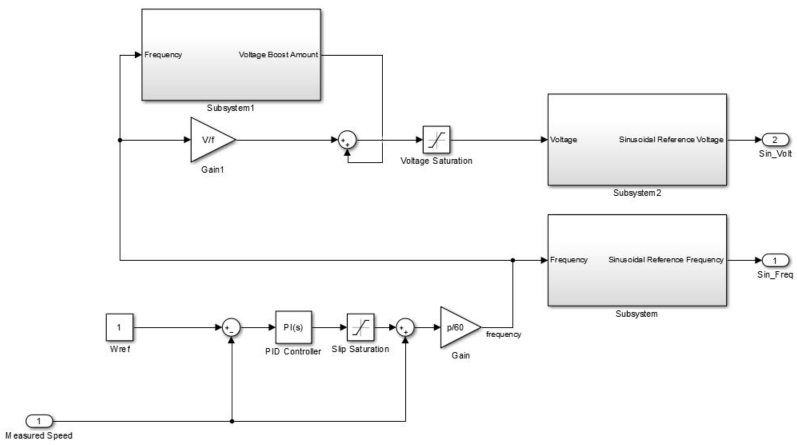


Figure 13: PWM VSI Closed Loop Constant Flux Control

To calculate the switching frequency , I thought the induction motor equivalent circuit as a LR circuit . Hence , I calculated circuit electrical time constant following this I calculated switching frequency. If we look R_{th} and X_{th} values from MATLAB script , we see that values are,

$$R_{th} = 1.3135 \text{ ,} X_{th} = 1.8072 \text{ , } X_2 = X_r = 1.4675 \text{ , } \frac{R}{s} \approx 1.3950(s = 1)$$

I found the value for s=1 case because in other case R will increase and $\frac{L}{R}$ value will be decrease but our limiter has the be the maximum value of the this time constant . To find the L values I divided X_{equ} value to $2 * \pi * f$. As a result our , time constant was equal to ,

$$T_e = \frac{L}{R} = 3.85ms$$

To establish $T_e >> T_s$ relation , I chose the switching frequency $f_s \approx 10kHz$.

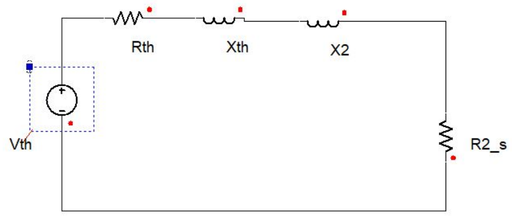


Figure 14: Thevenin Equivalent Circuit of the Induction Motor (Per/Phase)

I chose the L and C value to be able to decrease the ripple to 2%, so the L value is 1 mH and C value is 5 mF . As a switch for inverter I used MOSFET because the induction motor has low voltage and power rating ,so MOSFET can handle it . Also, to operate in higher frequency MOSFET will be more efficient than other semiconductor devices.

4 Part C

In this part, I tried to explain how is the performance of the open loop control driven driver and its response to low speeds. Also , by showing the calculations , I tried to give the calculation to find appropriate values.As a PWM method ,I used Space Vector Pulse Width Modulation Technique (SVPWM).

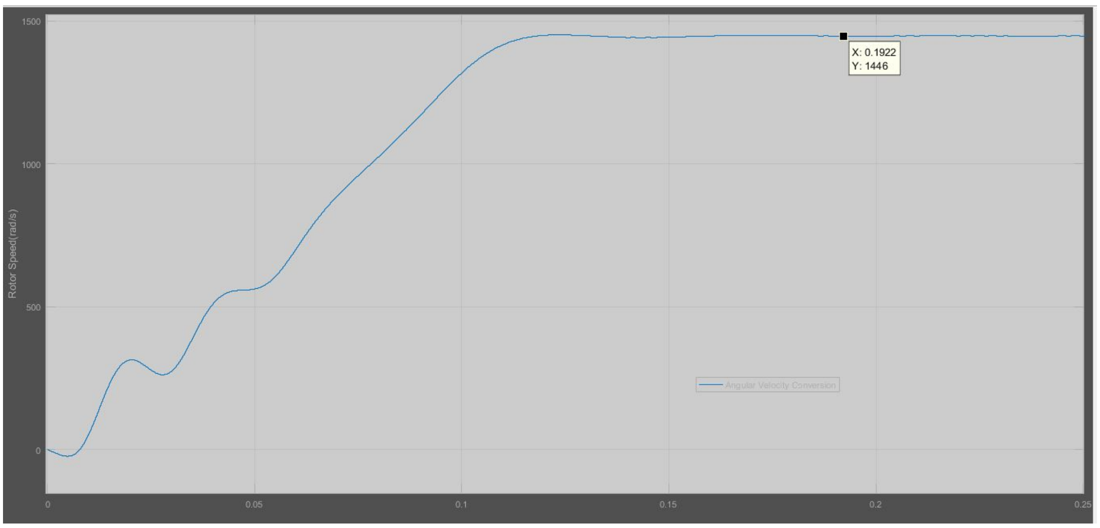


Figure 15: Speed of the Induction Motor at rated load,voltage and frequency

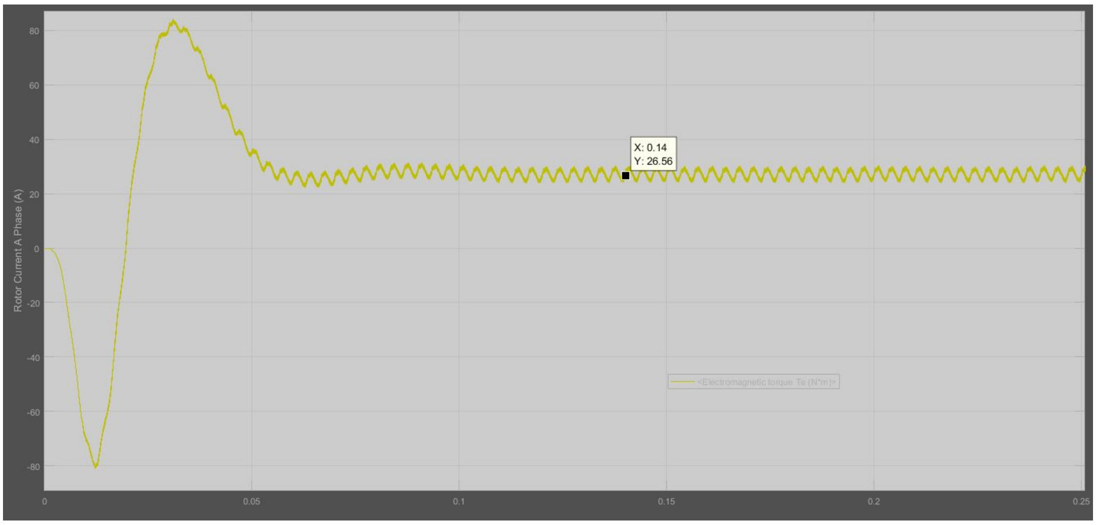


Figure 16: Torque of the Induction Motor at rated load,voltage and frequency

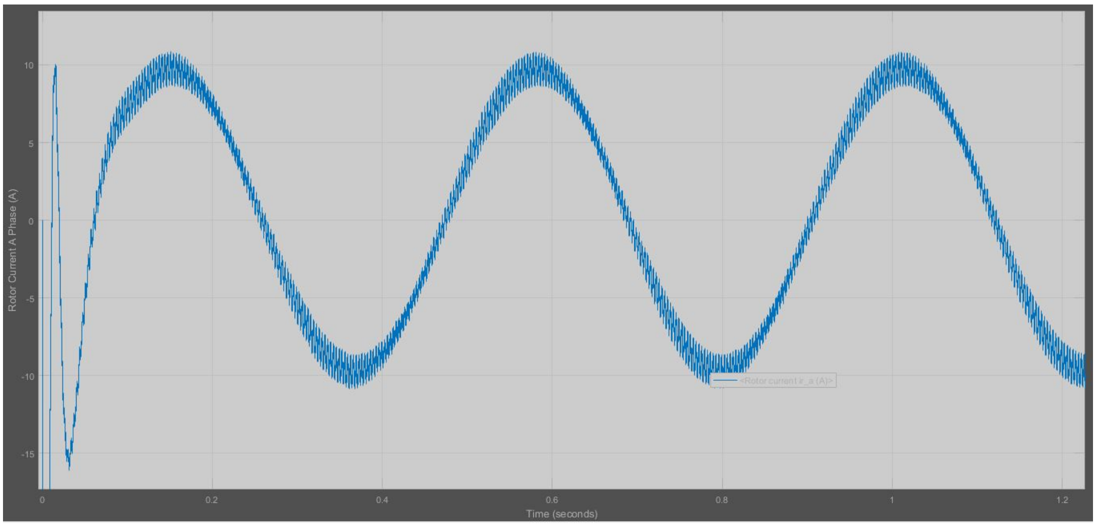


Figure 17: Phase A Current of the Induction Motor at rated load,voltage and frequency

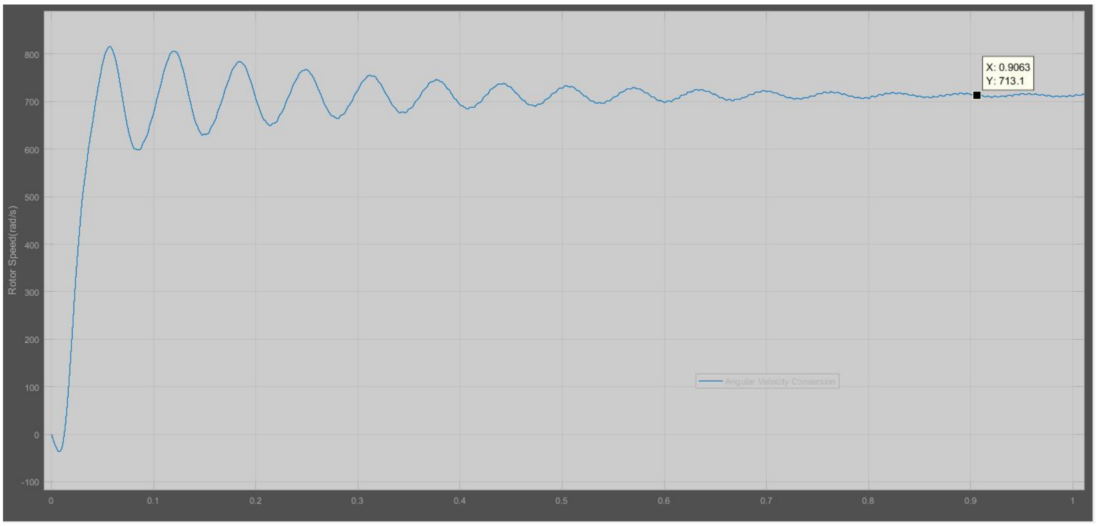


Figure 18: Speed of the Induction Motor at half of the rated load,voltage and frequency

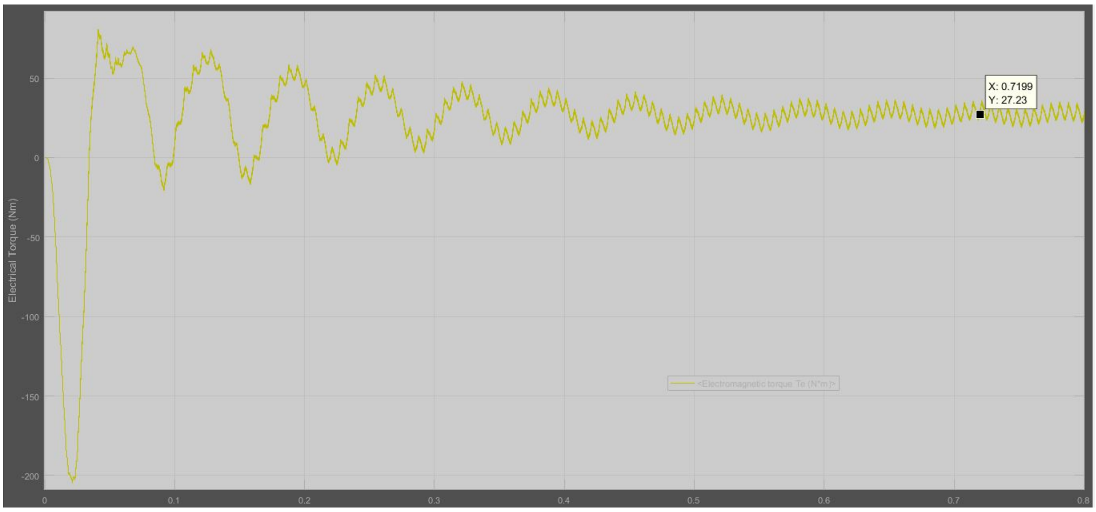


Figure 19: Torque of the Induction Motor at half of the rated load,voltage and frequency

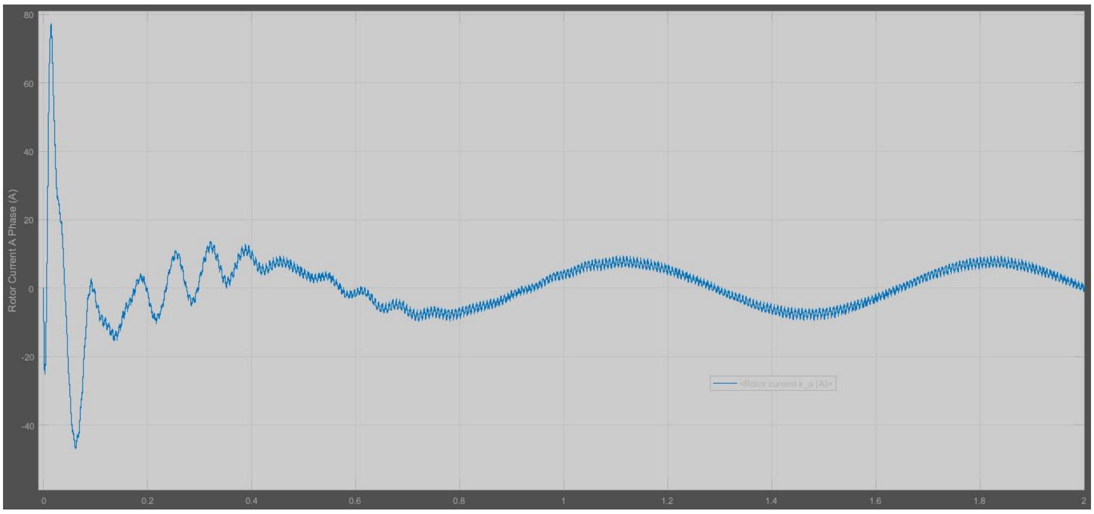


Figure 20: Phase A Current of the Induction Motor at half of the rated load,voltage and frequency

In figures 15 and 18,one can see that in 18 the ripple amount for current,torque and speed is more because when system has lower speed instantaneous change will become more significant and these will affect as a ripple on the torque,speed and current.

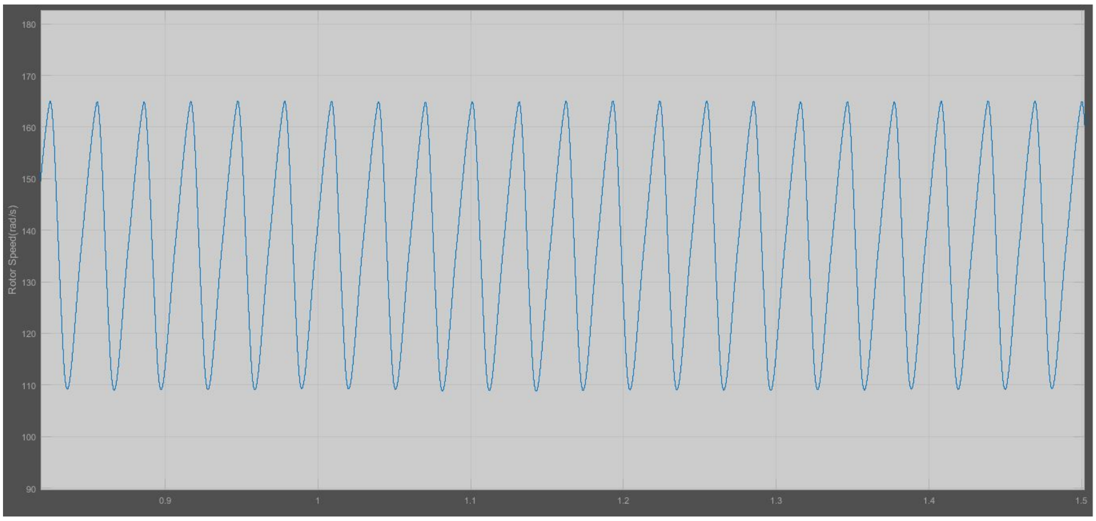


Figure 21: Speed of the Induction Motor at 0.1 full rated load,voltage and frequency

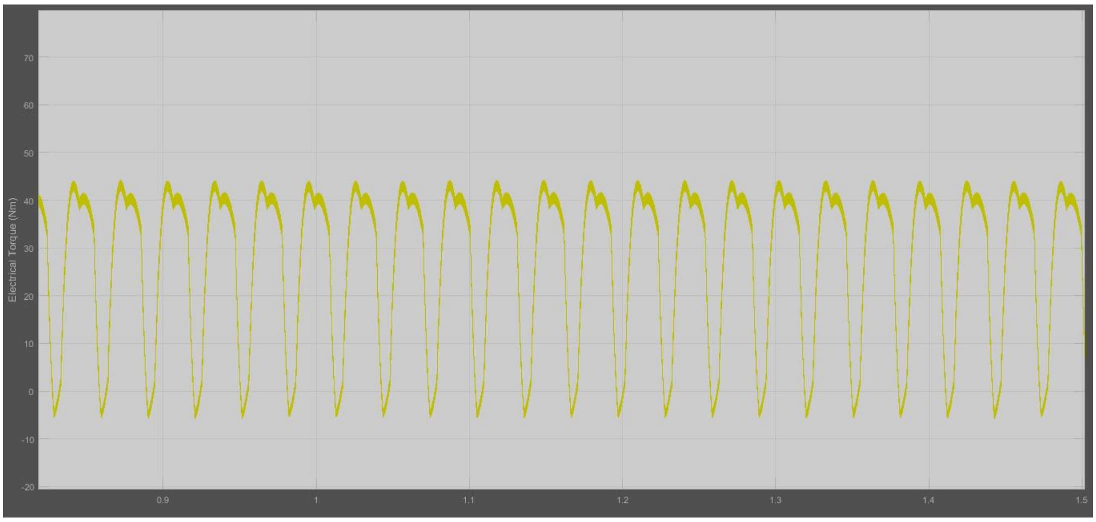


Figure 22: Torque of the Induction Motor at 0.1 full rated load,voltage and frequency

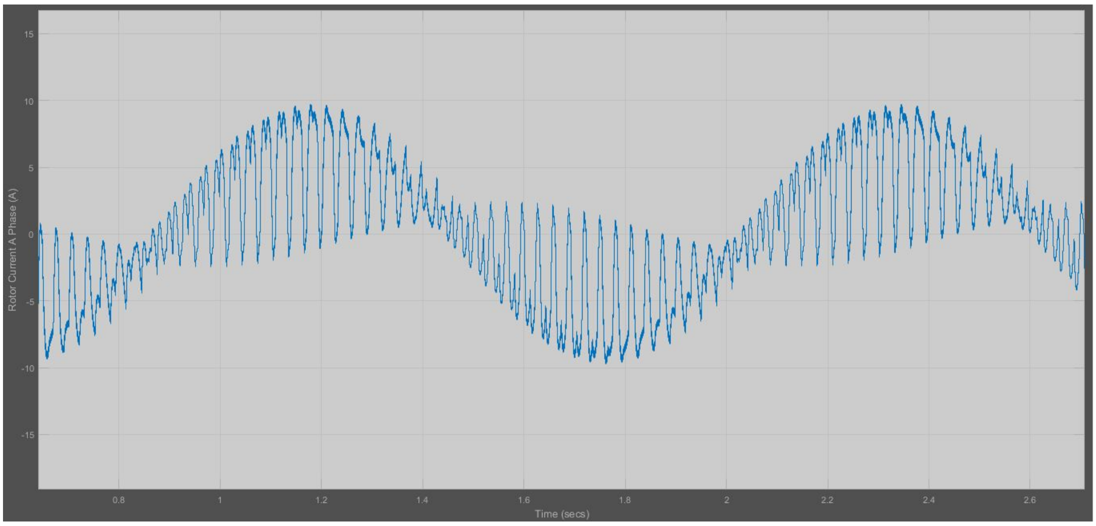


Figure 23: Phase A Current of the Induction Motor at 0.1 full rated load,voltage and frequency

To obtain the 0.1 pu rated speed,I did some calculations and so I find the value of frequency and voltage reference value.

- As I said before I used SVPWM , so to calculate the slip speed of the induction motor,first I find the rotor speed when $M_a = 1$,so I applied $M_a = 1$ and $f = 50Hz$ and n_r was 1480 rpm.

- Than I find the slip speed via , $n_{slip} = n_s - n_r$ and n_s value is equal to $\frac{120f}{p}$ so it is 1500 rpm and $n_{slip} = 20rpm$

- System 0.1pu rated value is equal to 143 rpm and if we add this slip speed value we find the necessary frequency of the system via calculating synchronous speed $n_{s_{0.1pu}} = 143 + 20 = 163rpm$ and the frequency is $f_{0.1pu} = \frac{n_{s_{0.1pu}} * p}{120}$ so it is equal to 5.433 Hz

- To find the voltage I multiplied frequency value with 400/50 and found the base voltage value and by using BoostVoltageCalculator I find the boost voltage value .After that, I added boost voltage value and base voltage value so I find the reference voltage value which is 72.834 V

- Than I calculated M_a by using SVPWM output voltage input voltage transfer ratio which is $V_{out} = \frac{M_a V_{dc}}{\sqrt{2}}$,and so the M_a value is equal to approximately 0.1073 and I applied these M_a and frequency value to the controller and I obtain figures 21-23 .

In figure 21-23, one can see that the ripple is too much because we are operating further from safely operating region so to keep system in appropriate torque has become much more dificult.

5 Part D

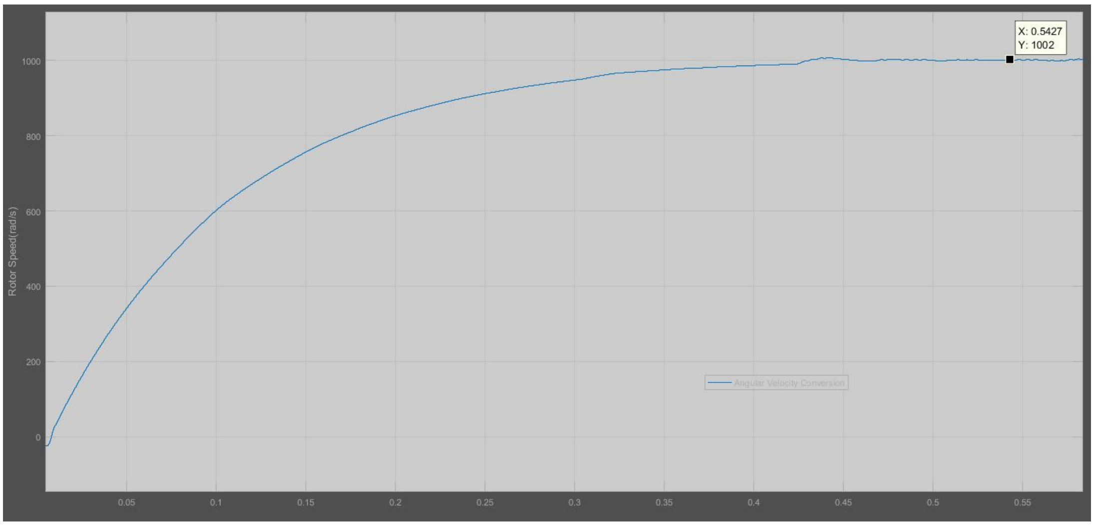


Figure 24: Speed of the Induction Motor at Closed Loop Control driven Driver and Rated Torque

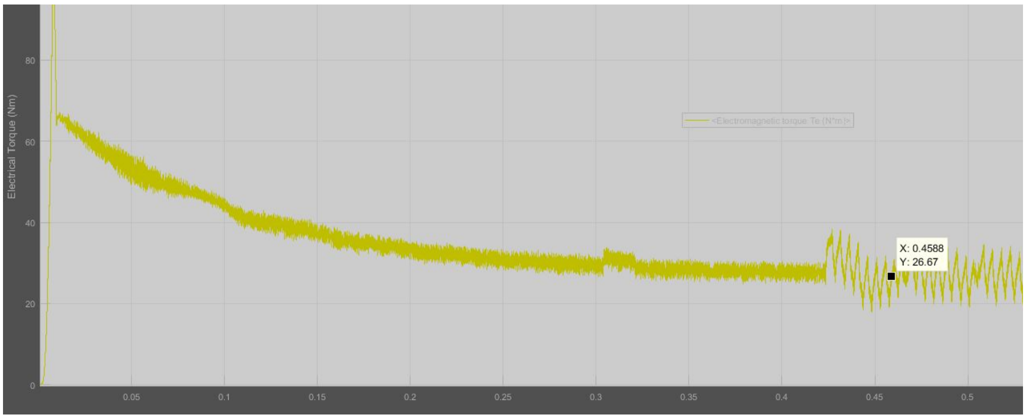


Figure 25: Torque of the Induction Motor at Closed Loop Control driven Driver and Rated Torque

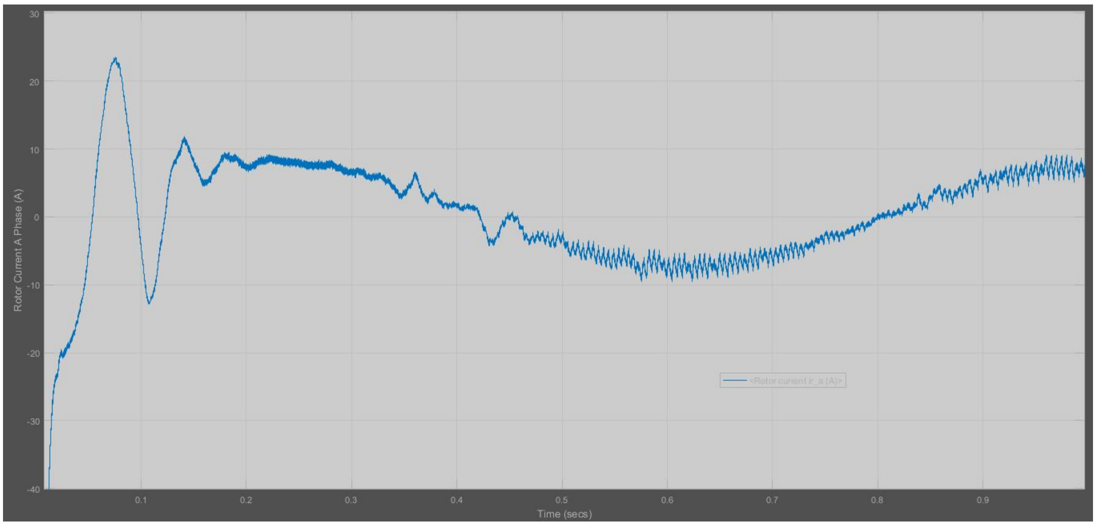


Figure 26: Current of the Induction Motor at Closed Loop Control driven Driver and Rated Torque

As explained in Power stages and Controller Part , the controller use a rotor speed as a feedback and its main objective is compensate the slip . Plus, the controller is creating the voltage and frequency reference with regards to SVPWM .So the operating coordinates are linear and PID will be more suitable for this operation. I used Adaptive PID control, to control each of the phase separately. For the beginning, to satisfy soft starting , P value was chosen small so the system was not increasing instantly. Then P,I and D values adjusted to handle ripple of the speed.

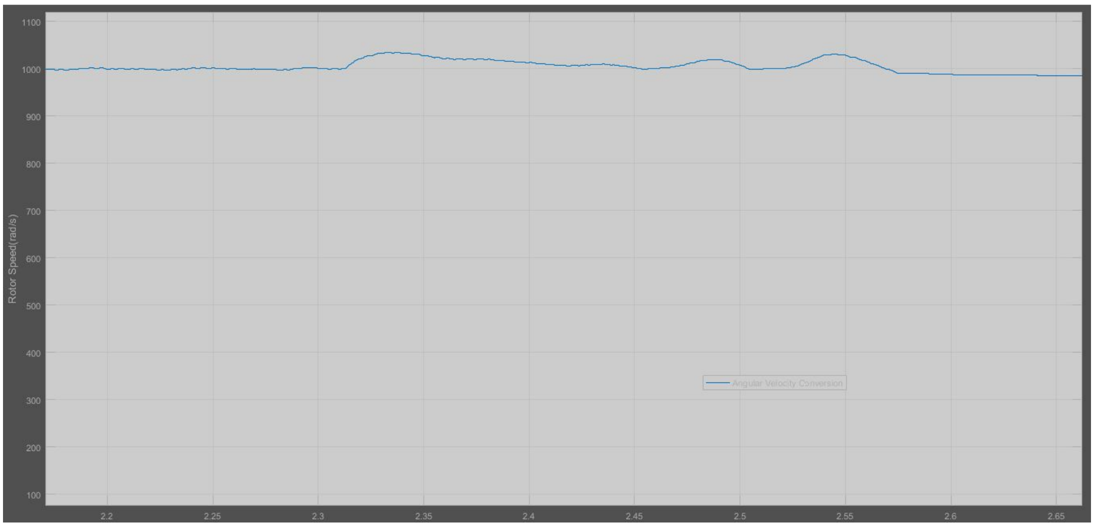


Figure 27: Speed of the Induction Motor at Closed Loop Control driven Driver and Rated Torque-No Load Transition

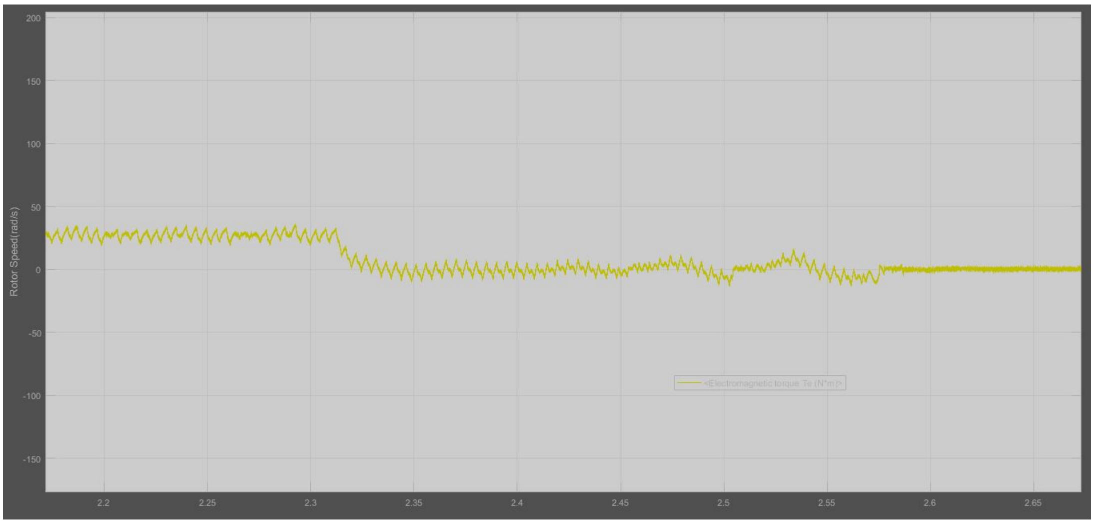


Figure 28: Torque of the Induction Motor at Closed Loop Control driven Driver and Rated Torque-No Load Transition

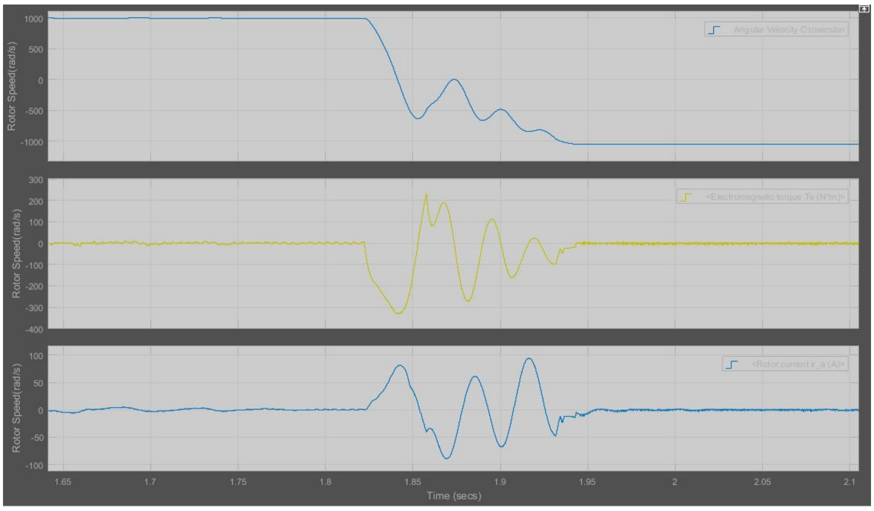


Figure 29: Induction Motor Parameters at Closed Loop Control driven Driver and No Load Rated Speed - (-) Rated Speed Transition

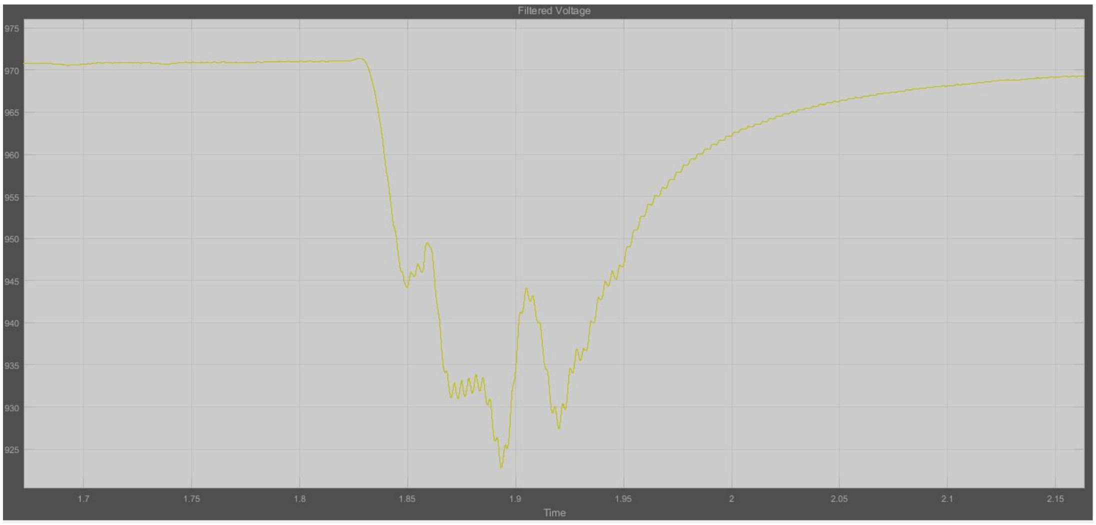


Figure 30: Applied Voltage at Closed Loop Control driven Driver and No Load Rated Speed - (-) Rated Speed Transition

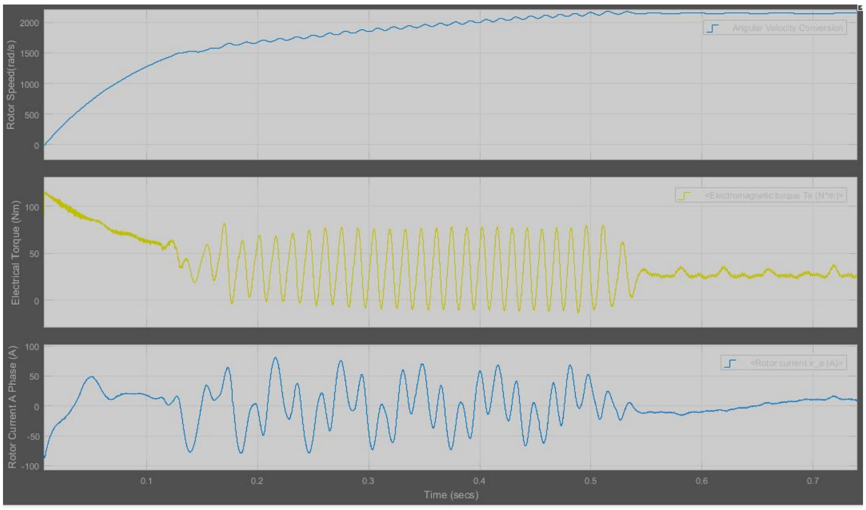


Figure 31: Induction Motor Parameters at Closed Loop Control driven Driver Flux Weakening Region

The controller is tested for different kind of operations. When there was instantaneous torque change from rated torque to no load the controller can handle speed control easily. To measure the speed bandwith of the system , I changed the reference speed from plus to zero instantaneously. The controller handled the speed control ,but for torque and current waveforms there is too much instant change and this will cause a huge stress on the components. Fortunately, the stress is for a while so the components will not be damaged too much .For field weakening region, there were too much ripples for the beginning because the PID values adjusted for soft starting able Constant Torque region ,so with some readjustment the ripple can be eliminated .To sum up , adaptive PID Control made system much more complex , but hopefully the controller can satisfy all the requirements and with a little adjustment the general ripple can be eliminated.

6 Part E

In this part I tried to explain the component selections with appropriate reasoning .Also,I try to verify that the system is not exceeding the rated values of the semiconductors by using simulation results.So, I approved the robustness of the system .

As I said before ,after increasing grid voltage level to 690 line to line rms ,I changed my semiconductors from MOSFET to IGBT.The chosen IGBT is IXDH 20N120 (Appendix B) and it is Non Punch Through IGBT .

The most important ratings of IXDH 20N120 are,

- $V_d = 1200V$ blocking voltage (Continuous and Discrete Same) : I took the maximum value 1200 V ,because if motor is decelerating , the dynamic braking resistance is opening after 1150 V value .

- $I_d = 34A$ average forward current

- $I_d = 90A$ discrete forward current

If we look figures 32-33,one can see that the maximum voltage on the IGBT will be each PWM period max voltage ,and it is approximately 960 V . Also,the maximum current on the IGBT is 10A . As a result, we can approve that the IGBT will be not harmed from inverter nominal operation.

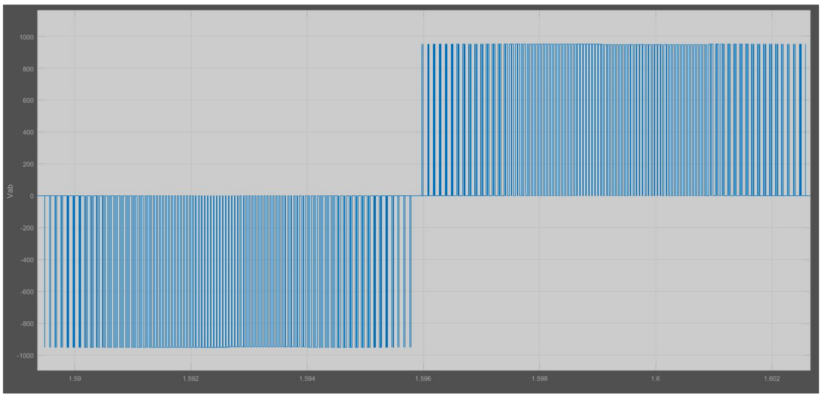


Figure 32: Line To Line Voltage of the Inverter

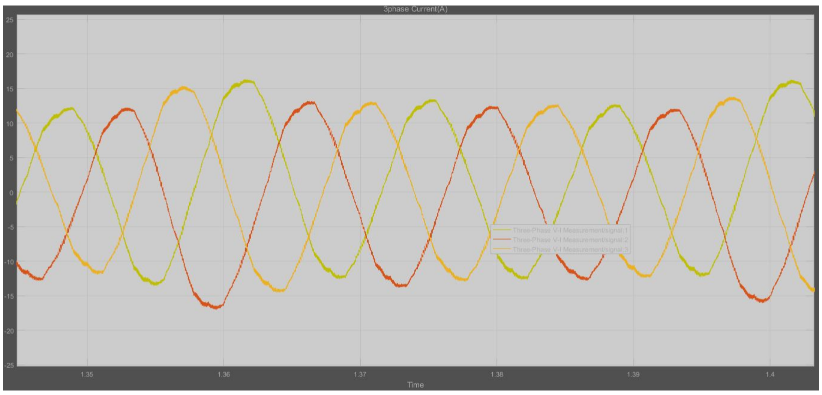


Figure 33: Current Output of the Inverter

7 Part F

In this part ,I tried to explain loss characterization of the system and efficiency of the system. As a loss, I focused on inverter IGBT losses which are conduction and switching.I calculated them via datasheet of the IGBT and simulation results. After calculating each of them , I find the efficiency of the inverters.

$$P_{sw} = E_{on} E_{off} f_s \tag{12}$$

P_{sw} is switching losses and if we consider IXDH 20N120 datasheet E_{on} is equal to 3.1 mJ and E_{off} is approximately 2.4mJ .If we multiply them with f_s which is 10 kHz ,our result will be 55 W. P_c which is conduction losses is equal to $P_c = I_{avg} V_{ce_{sat}}$ where $V_{ce_{sat}}$ is 2.4V , I_{avg} is 4.18A ,so it is approximately 12W .

$$P_{tot} = P_{sw} + P_c \tag{13}$$

As a result, the total loss of the 3Θ inverter is 6 times of the total loss of the each IGBT and it is approximately 0.402 kW . If we want to calculate the efficiency,

$$n_{inverter} = \frac{P_{out}}{P_{tot} + P_{out}} \tag{14}$$

Where P_{out} is the output power of the inverter and can be calculated via,

$$P_{out} = 3V_{ln_{rms}} I_{ln_{rms}}(15)$$

If system's $V_{ln_{rms}} 424V$ and $I_{ln_{rms}=7A}$,so system P_{out} is approximately 9 kW. As a result, inverter efficiency will be approximately 96%.

To calculate the overall efficiency and also the motor efficiency has to be calculated. Motor efficiency depends on , motor output power and mechanical losses.So,motor efficiency will be ,

$$n_{motor} = \frac{T_{out} w_r}{(T_{out} w_r + I^2(R_{stator} + R_{rotor})} \tag{16}$$

So n_{motor} is equal to approximately , 93% and overall efficiency is equal to multiplication of n_{motor} and $n_{inverter}$. The result is equal to approximately , 89.5%.

8 Part G

In this part , Firstly , I will explain to you the Field Oriented Control analytically .Than, I will briefly give some information about FOC block such as how the SimuLink schema working and what are the most important parameters.To obtain important parameters of the FOC ,I used Simulink AC3 drive example. Thanks to Mathworks, I did not constructed Field Oriented Controller from the very beginning. I used AC3 drive example of SimuLink . I only changed the PID values,saturation limits and motor parameters. These important parameters are , speed regulation capability or in other words speed bandwith of the driver and soft starting algorithm of the driver. Lastly, I will compare FOC and Slip Compensation .

8.1 What is Field Oriented Control(FOC)

Until now , we see different kind of closed loop control strategies to drive the AC machines. One of the most common used classic closed loop control method is sinusoidal commutation based AC motor controller. This method, apply three 120 degree spatially displaced sinusoidal voltages to each stator phases.These three different sine waves are based on motor steady state equivalent model ,so it is not focusing on transient region of the controller. This type controller has to behave to the each stator phase of the motor differently because applied per phase stator voltages are not same . So there is not solid connection between each stator phase controller.As a result, there are some disadvantages that we can not prevent. These disadvantages are,

- It is not concerning transient of the system , so this causes some high current and voltage ripples on the devices such as semiconductors and connection cables and motor itself.It is device unfriendly.
- The controller based on sinusoidal voltages ,so without damaging sinusoidal voltages PID controller can not be applied because PID is based on linear mode of operations
- The controller highly depend on steady state equivalent circuit of the motor,so it can not applied every kind of motor easily. Whenever, the motor change some of the control parameters has to be changed

To overcome these kind of disadvantages ,we have to change our perspective to the control method entirely. We have to convert our AC motor topology to DC motor topology because DC machine is such that the field flux is perpendicular to the armature flux.So, these two fluxes can be controller individually. Changing the field current will change the flux,on the other hand changing the armature current will change the torque of the motor.However , AC machine has not so simple relations because interactions between stator and the rotor fields are not held at 90,but they vary with the operating conditions. As a result, one of the components have to behave according to other component . To obtain DC machine-like performance the stator current orienting with respect to the rotor flux so flux and torque can controlled independently.Such a control called Field Oriented Control or Vector Control , and it is applicable for all kind of AC machines. Field oriented control is operating in d-q axis which is the decomposition of the 3Θ to the orthogonal currents as decomposing power to reactive and active power . In this case , active current is the Torque generator current and reactive current is field current. The conversions simply explained in figure 35 .

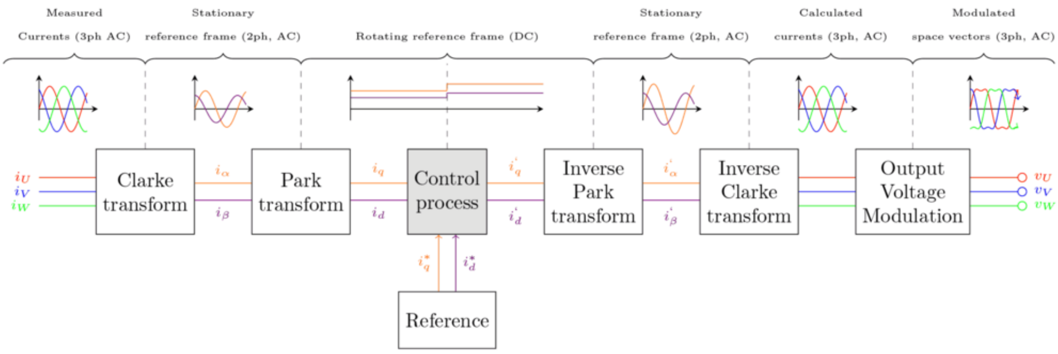


Figure 34: General Schematic of Field Oriented Controller

To apply FOC , I used MatLab $ac3_example$, I could not add the result because I could not finish it completely.I want to do the comparison with regards to my observations. FOC can achieve better transition because it care of all of the phases of the system . So for instantaneous speed reference change ,it solves the problems exactly the ripple problem very easily even without any ripple.

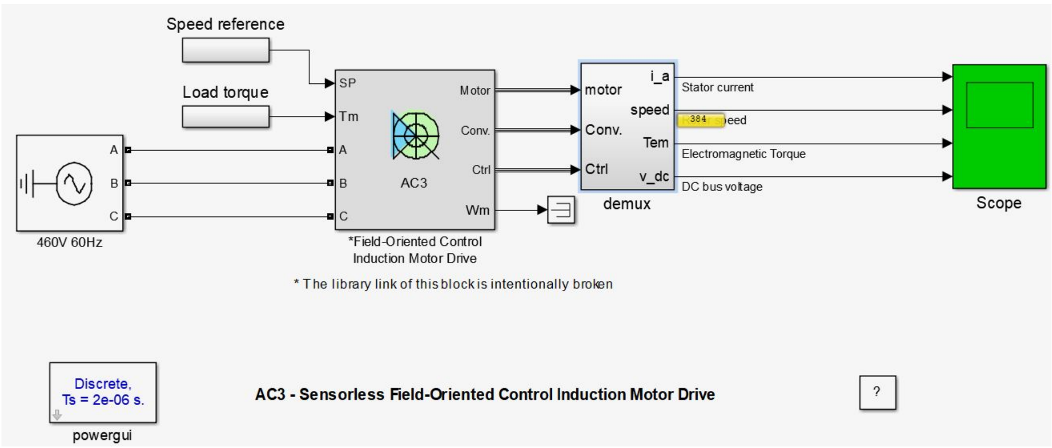


Figure 35: General Schematic of FOC MatLab

9 Appendices

9.1 Appendix A - BoostVoltageCalculator

```
function boost = fcn(freq)
    boost = 0 ;
    %Voltage Boost Calculator

    TMax = 91.0303 ; %Max Torque calculated via rated Values

    Ls = 5.839e-3 ; %Stator Inductance Henry
    Lm = 0.1722 ; % Magnetization Inductance Henry
    Lr = 5.839e-3 ; % Rotor inductance Henry
    Rs = 1.405 ; % Stator resistance ohm

    VRated = 230 ;
    frated = 50 ;
    p =4 ;
    if (freq ~= 0) && (freq < 50)
        constant = 50/freq;
        fRated = frated/constant;

        ws = 2*pi*fRated/(p/2);

        Xs = Ls*2*pi*fRated ;
        Xr = Lr*2*pi*fRated;
        Xm = Lm*2*pi*fRated;

        Zth = (-Xm*Xs+1i*Rs*Xm)/(Rs+1i*(Xs+Xm));
        Rth = real(Zth);
        Xth = imag(Zth);

        %To find how much voltage we have to boost,I used our maximum torque value
        %So I derived needed thevenin voltage for current frequency
        Vboost_1 = sqrt(complex(TMax*(2*ws*(Rth+sqrt(Rth^2+(Xth+Xr)^2)))/3));
        Vboost_2 = Vboost_1*(Rs+1i*(Xs+Xm))/(1i*Xm)-VRated/constant;

        boost= real(Vboost_2);
    else
        return
    end
end
```

9.2 Appendix B - IGBT Datasheet

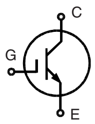
IXYS

High Voltage IGBT with optional Diode

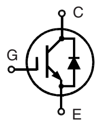
IXDH 20N120
IXDH 20N120 D1

V_{CES} = **1200 V**
I_{C25} = **38 A**
$V_{CE(sat)\,typ}$ = **2.4 V**

Short Circuit SOA Capability
Square RBSOA

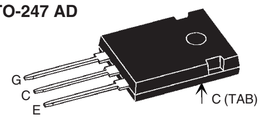


IXDH 20N120



IXDH 20N120 D1

TO-247 AD



G = Gate, E = Emitter
C = Collector , TAB = Collector

Symbol	Conditions		Maximum Ratings	
V_{CES}	T_J = 25°C to 150°C		1200	V
V_{CGR}	T_J = 25°C to 150°C; R_{GE} = 20 kΩ		1200	V
V_{GES}	Continuous		±20	V
V_{GEM}	Transient		±30	V
I_{C25}	T_C = 25°C		38	A
I_{C90}	T_C = 90°C		25	A
I_{CM}	T_C = 90°C, t_p = 1 ms		50	A
RBSOA	V_{GE} = ±15 V, T_J = 125°C, R_G = 82 Ω Clamped inductive load, L = 30 µH		I_{CM} = 35 V_{CEK} < V_{CES}	A
t_{SC} **(SCSOA)**	V_{GE} = ±15 V, V_{CE} = V_{CES}, T_J = 125°C R_G = 82 Ω, non repetitive		10	µs
P_C	T_C = 25°C	IGBT Diode	200 75	W W
T_J			-55 ... +150	°C
T_{stg}			-40< ... +150	°C
Maximum lead temperature for soldering 1.6 mm (0.062 in.) from case for 10 s			300	°C
M_d	Mounting torque		0.8 - 1.2	Nm
Weight			6	g

Features

- NPT IGBT technology
- low saturation voltage
- low switching losses
- square RBSOA, no latch up
- high short circuit capability
- positive temperature coefficient for easy paralleling
- MOS input, voltage controlled
- optional ultra fast diode
- International standard package

Advantages

- Space savings
- High power density

Typical Applications

- AC motor speed control
- DC servo and robot drives
- DC choppers
- Uninteruptible power supplies (UPS)
- Switch-mode and resonant-mode power supplies

Symbol	Conditions		Characteristic Values (T_J = 25°C, unless otherwise specified) min.	typ.	max.	
$V_{(BR)CES}$	V_{GE} = 0 V		1200			V
$V_{GE(th)}$	I_C = 0.6 mA, V_{CE} = V_{GE}		4.5		6.5	V
I_{CES}	V_{CE} = V_{CES}	T_J = 25°C T_J = 125°C		 2	1 	mA mA
I_{GES}	V_{CE} = 0 V, V_{GE} = ±20 V				± 500	nA
$V_{CE(sat)}$	I_C = 20 A, V_{GE} = 15 V			2.4	3	V

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