Title: Combined power control of a grid connected 1.5 MW PMSG based wind turbine

-Grid side converter design, control and synchronization with the grid.

-Virtual inertia control of WT

submitted on 21.11.2020 –

by

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Statutory Declaration

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Hereby I declare on oath, that I, Md.Nura Alam, have authored in- dependently this report with the title **''Combined power control of a grid connected 1.5MW PMSG based wind turbine''** and did not use any other means than indicated. The parts of the work which have been taken in the wording or meaning of other works are indicated in each case with naming of the original reference.

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0 Introduction

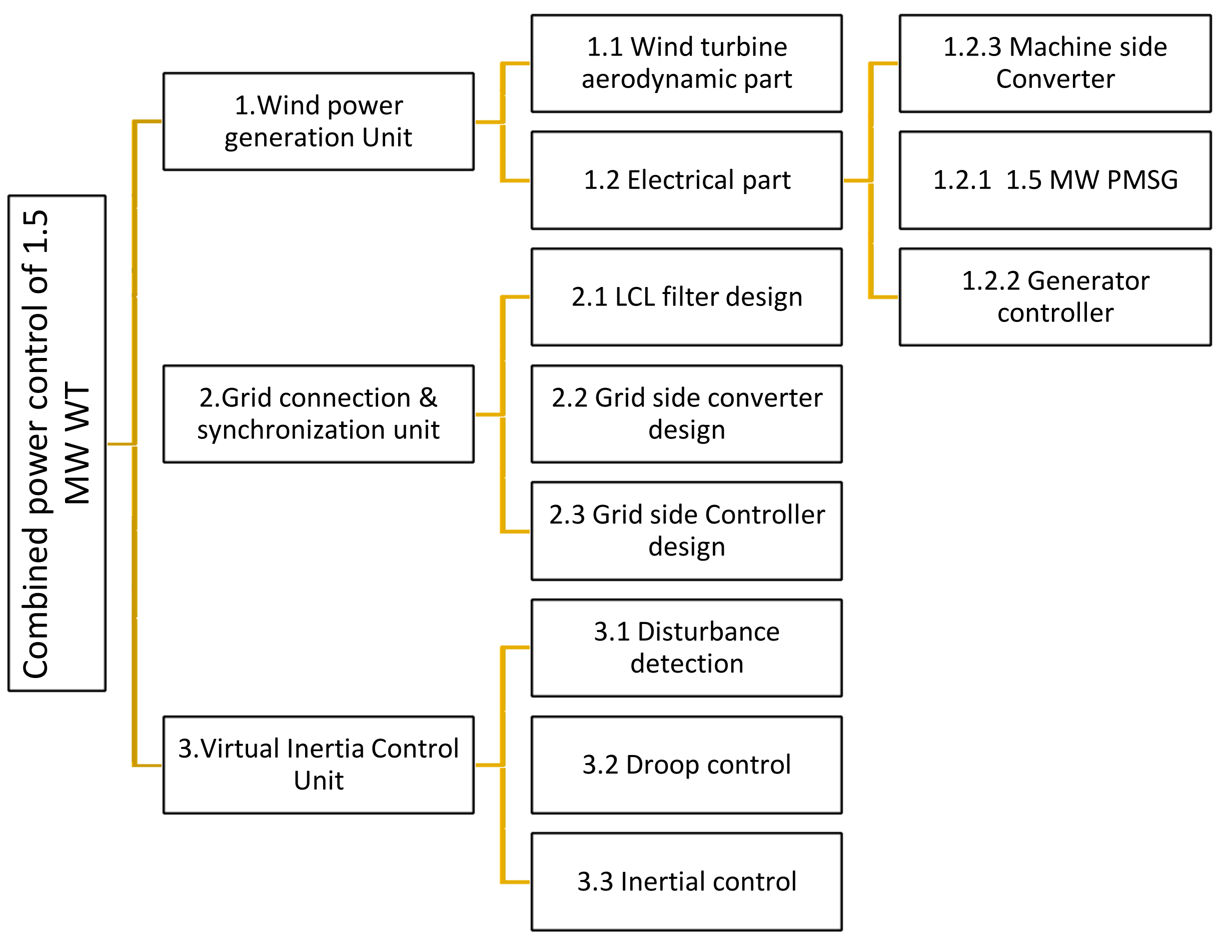
This master thesis is dealing with the combined power control of the 1.5MW PMSG based wind turbine using virtual inertia control mechanism. The whole report is divided into three parts. They are –

a) The power generation unit(From wind turbine to dc link capacitor): It generally deals with wind turbine part where the generator gets the mechanical power upon which it generates the electrical power and supplies that power to the dc link capacitor. This section consists the wind turbine, generator, a machine side converter and a generator controller.

b) The power synchronization unit with the grid(From dc link capacitor to Grid): The grid side converter takes power from the dc link capacitor and supplies that power to the grid according to the condition of the grid. Particularly, this part involves a suitable inverter, a filter for the synchronization and a controlling section on which the converter is controlled.

c) The virtual inertia control unit: This section discusses about the power control of the wind turbine. Like the conventional steam turbine power plant synchronous generator it responds to grid disturbances. Disturbance detection, droop control, inertia controller are the main agenda of this section.

The whole thesis discussion points are presented diagrammatically below for better visualization.



1 Wind power generation unit

A wind turbine converts the wind energy into electricity. The air pressure in the wind turbine blades faces of different level in the turbine blades and for this reason the blade got a lift and a drag force. The lift force helps the turbine blade to rotate. The turbine shaft is connected with the prime mover of a generator. Between the rotor of the generator and turbine there is a gear box placed which in turn makes the low speed of the blade to a higher speed in the generator side. Thus, the acronymic force of the wind creates electricity in the generator [9]

The sample block diagram of wind power generation is shown below in diagram. In the left side the green block represents the wind turbine. The FAST software has been implemented here to realize the wind turbine model. The generator block on right side is generating the electrical power and charging the dc link capacitor as indicated in the figure. In the next section the two blocks will be explained in details.

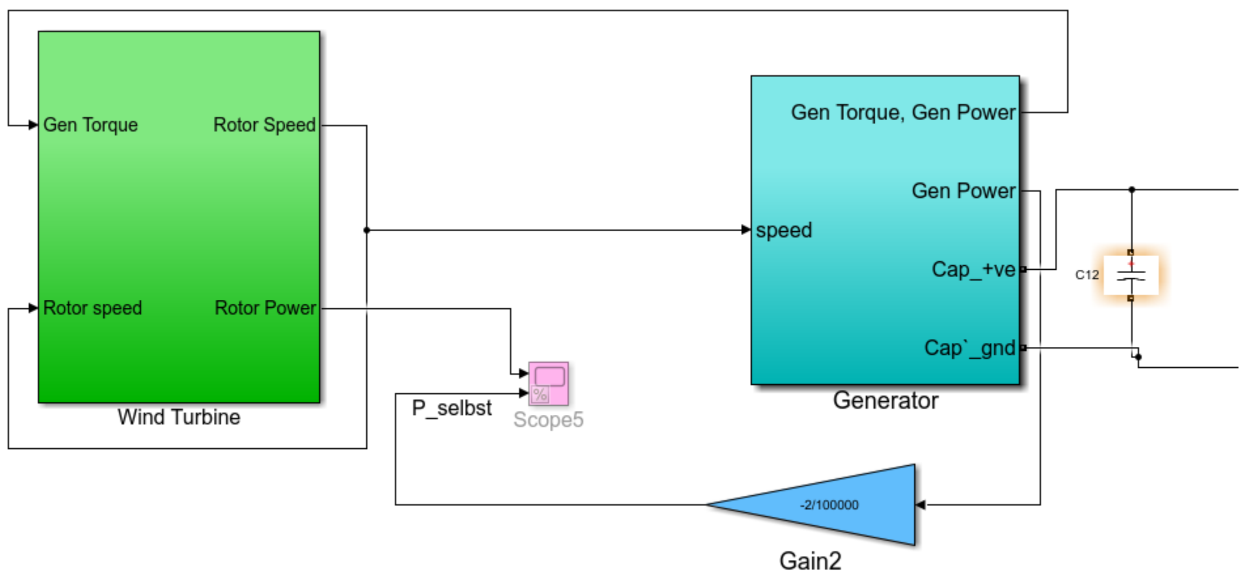


Figure 1: Wind power generation block diagram

1.1 wind turbine aerodynamic part

As mentioned in the previous section to simulate aerodynamic model of a wind turbine FAST software has been used. Three bladed wind turbine has been considered here. The main advantage of using FAST libraries to realize a wind turbine is that there are 24 DOFs (Degree of freedom) here. It means that 24 parameters can be controlled here to see the behavior of the model when it is in 24 different conditions. This feature makes this analysis of this thesis more realistic and unique. The 24 DOFs includes 3 translational (surge, sway and heave) motions ,3 rotational motions(roll, pitch, yaw) of support platform, four tower motion DOFs, two longitudinal modes, two lateral modes, one DOF for yawing motion, one for the generator azimuth angle, another DOF is the compliance in the drivetrain between the generator and hub/rotor, three DOFs are the blade flap wise tip motion, three DOFs are for the blade edgewise tip displacement and finally the last two DOFs for rotor and tail furl. [10]

1.2 Electrical part

After getting the torque from the wind turbine the generator rotor rotates and generates power to the stator of the generator. Then, a suitable machine side converter transports this power to the dc link capacitor. There is a controller mounted on the generator to control the torque, currents. The internal architecture to simulate the **Generator** block of Figure 1 mentioned above is shown below in details in Figure 2.

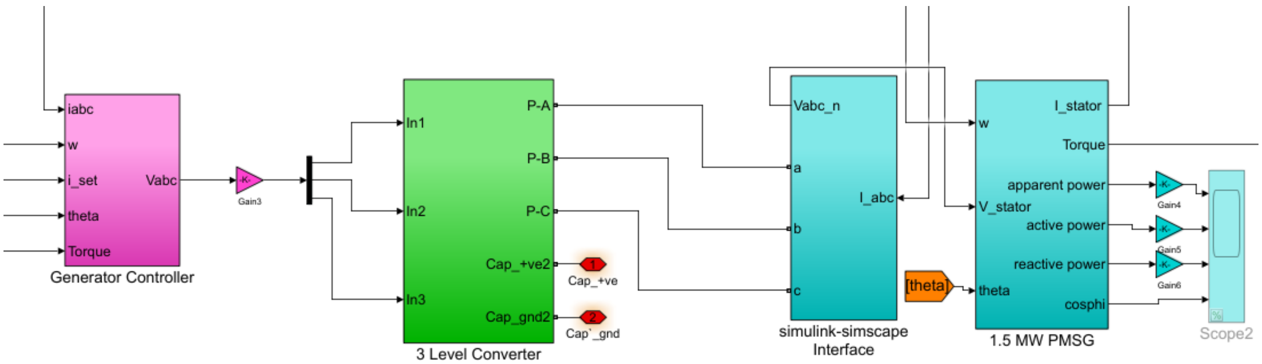


Figure 2: Electrical part Simulink block

In the following sections the 1.5MW PMSG with it's specification, Simulink block has been discussed first, then the transfer function has been calculated with the specifications. After that, the machine controller of this machine has been described and the controller tuning procedure is explained in details. Then the simulink to simscape interfacing has been described. Finally, a machine side converter for this generator has been elucidated.

1.2.1 1.5 MW PMSG

The excitation field is provided by permanent magnet in PMSG. It operates at a synchronous speed since the rotor and the magnetic field revolves at the same speed. [11]

The main advantage of this type of generator is it can operate at a full speed range, there is no gear needed for this kind of generator. Additionally, the real and the reactive power can be controlled here, it is brushless so there is not too much maintenance required. The field excitation is coming from the permanent magnet so no power converter is required for the field. However, there are some limitations also of this generator. The number of poles are many so it is little bit bulky and big. Lot of permanent magnets are needed for the field excitation. [12]

The dynamic equation in the dq coordinate system of the PMSG is shown below:

$$V_d = R * I_d + L_d * \frac{dI_d}{dt} - w * L_q * I_q \tag{1}$$

$$V_q = R * I_q + L_q * \frac{dI_q}{dt} + w * L_d * I_d - w * \Phi_f \tag{2}$$

$$T_{em} = \frac{3}{2} * [(L_d - L_q) * I_d * I_q - \Phi_f * I_q] \tag{3}$$

Where,

V_d, V_q, I_d, I_q =d & q axis voltage and current, L_d, L_q=d, q axis inductances,

w=angular velocity of the rotor, Φ_f=induced flux,

T_{em}=Electrical torque generated in the machine.

From the equations 1-3 the simulink block diagram of the PMSG has been shown in Figure 3 below.This is the internal architecture of 1.5MW PMSG block shown in Figure 2.

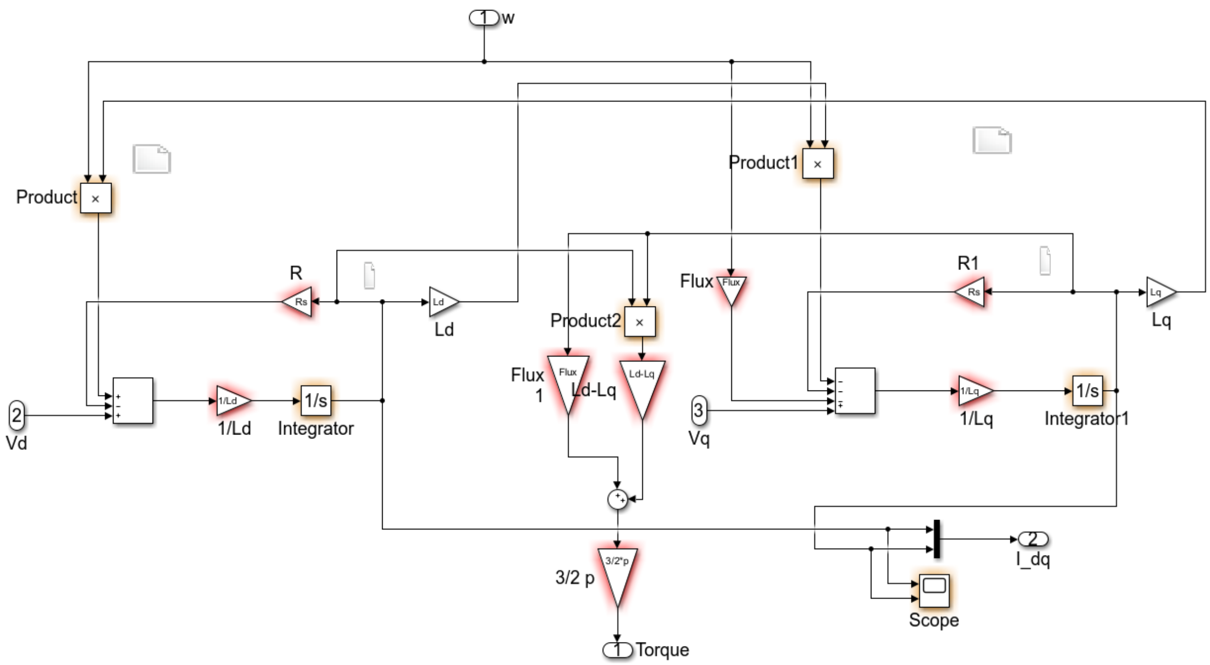


Figure 3: Simulink block diagram of PMSG (internal architecture of 1.5MW PMSG of Figure 2)

d loop transfer function:

In PMSG the input is the voltage Vd and Vq and the corresponding output is the currents Id and Iq. So, taking Laplace transformation of equation 1-

$$V_d = R * I_d + s * L_d \; - w * L_q * I_q$$

For simplification the last term of the equation above w*Lq*Iq is not considered here since it will be cross coupled in the controller design. Now, the equation becomes-

$$V_d = I_d * (R + s * L_d)$$

$$=> \frac{I_d}{V_d} = \frac{1}{(R + s * L_d)}$$

This is the open loop transfer function for d loop.

q Loop transfer function:

Taking the Laplace transformation of equation 2 above-

$$V_q = R * I_q + L_q * s * I_q + w * L_d * I_d - w * \Phi_f$$

In the same way above mentioned the last two terms of the equation above has been eliminated for simplification since the both of them would be cross coupled in the controller design. Hence, the equation becomes-

$$V_q = R * I_q + L_q * s * I_q$$

$$=> \frac{I_q}{V_q} = \frac{1}{R + s * L_q}$$

This is the open loop transfer function of the q loop.

It is seen that in both cases d and q loop the transfer function is identical because the d and q axis reactances L_d and L_q are equal(mentioned in Table 1).

In general the open loop transfer function of the PMSG is-

$$TF_{PMSG} = \frac{1}{s * L_d + R}$$

In order calculate the exact numerical transfer functional values the parameter of the PMSG has been mentioned below:

Table 1: Parameters of the 1.5 MW PMSG [3]

Parameter name	Parameter value	Parameter name	Parameter value
Pole pair, p	26	Flux, Φ_f	5.8264 Wb
d axis inductance, Ld	0.001575 H	Resistance, R	0.000821 Ω
q axis inductance, Lq	0.001575 H		

$$G_p = \frac{1218}{1.91s + 1}$$

Where, Gp =Open loop transfer function of the PMSG.

1.2.2 Generator controller

The main goal of using generator controller is to control the current, voltage, torque, speed and power. The control parameter can be subdivided into two categories. They are inner loop parameter and outer loop parameter. The inner loop consists only the currents while the outer loop consists torque, power, dc link voltage and speed. The inner loop current control system has two components: id and iq, they are already explained in *1.2.1 1.5 MW PMSG*

The relationship between inner and outer loop is shown in figure below:

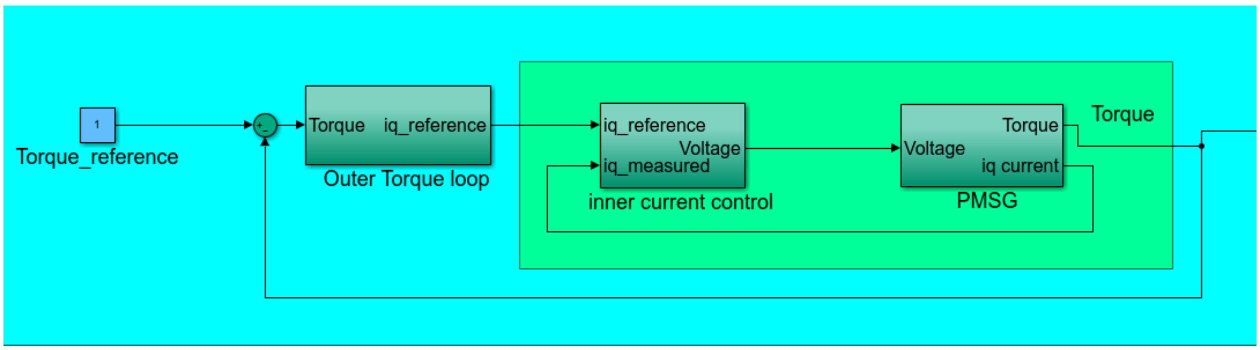


Figure 4: Inner and outer loop block diagram (green colored area is the inner loop and cyan colored is the outer loop)

The inner and outer loop is shown in the Figure 4 above. The green colored area is the inner loop while the cyan colored is the outer loop. The outer loop parameters generates the references for the inner loop. For example, the torque controller shown in Figure 4 generates the iq current reference and sends it to the iq controller. The iq controller supplies current to the PMSG according to this reference value and hence the torque is controlled in this way.

1.2.2.1 Inner current control loop

In this section first the transfer function calculation code will be presented. Then, the corresponding step response will be shown. From the step response of the plant the controller gain will be calculated. After that the Simulink block of the controller section will be explained in details and finally the simulation result of the controller will be explained graphically.

Controllers tuning general process:

Step 1:

Formulation of the transfer function from mathematical equation.

Step 2:

Plotting of the transfer function by using matlab command sisotool.

Step 3:

Putting the controller tuning specifications in the controller plot.

Step 4:

Opening the tuning method from control system designer app.

Step 5:

Choosing of the controller type and calibrate the values and observe the nature of the response.

Step 6:

Once the desired output is found then the corresponding controller parameter is noted down and put in the controller to check the performance.

The process mentioned above will be explained in details with pmsg controllers.

Current controller tuning for PMSG:

Step 1:

From mathematical calculation the transfer function of the current controller loop is:

$$tf\_pmsg = \frac{1218}{1.91s + 1}$$

Sample matlab code to formulate the transfer function in the command window:

```
R=0.000821;
Ld=0.001575;
Lq=0.001575;
mn=60000;
%transfer function of pmsg
num_pmsg=[1];
den_pmsg=[Ld R]*mn;
tf_pmsg=tf(num_pmsg,den_pmsg);
```

Output:

tf_pmsg =

```
      1
  --------------
  94.5 s + 49.26
```

Step 2:

The transfer function is run in the matlab command window. Next, a matlab command to call the sisotool is executed in the command window.

Sisotool(tf_pmsg)

Step 3:

When the command is executed then a step plot will be appeared in a new window shown in Figure 5.In that window the bode plot and root locus plot will also appear along with it but only the step plot is considered. The mouse cursor is put in step plot and the right button is clicked, a new option will be

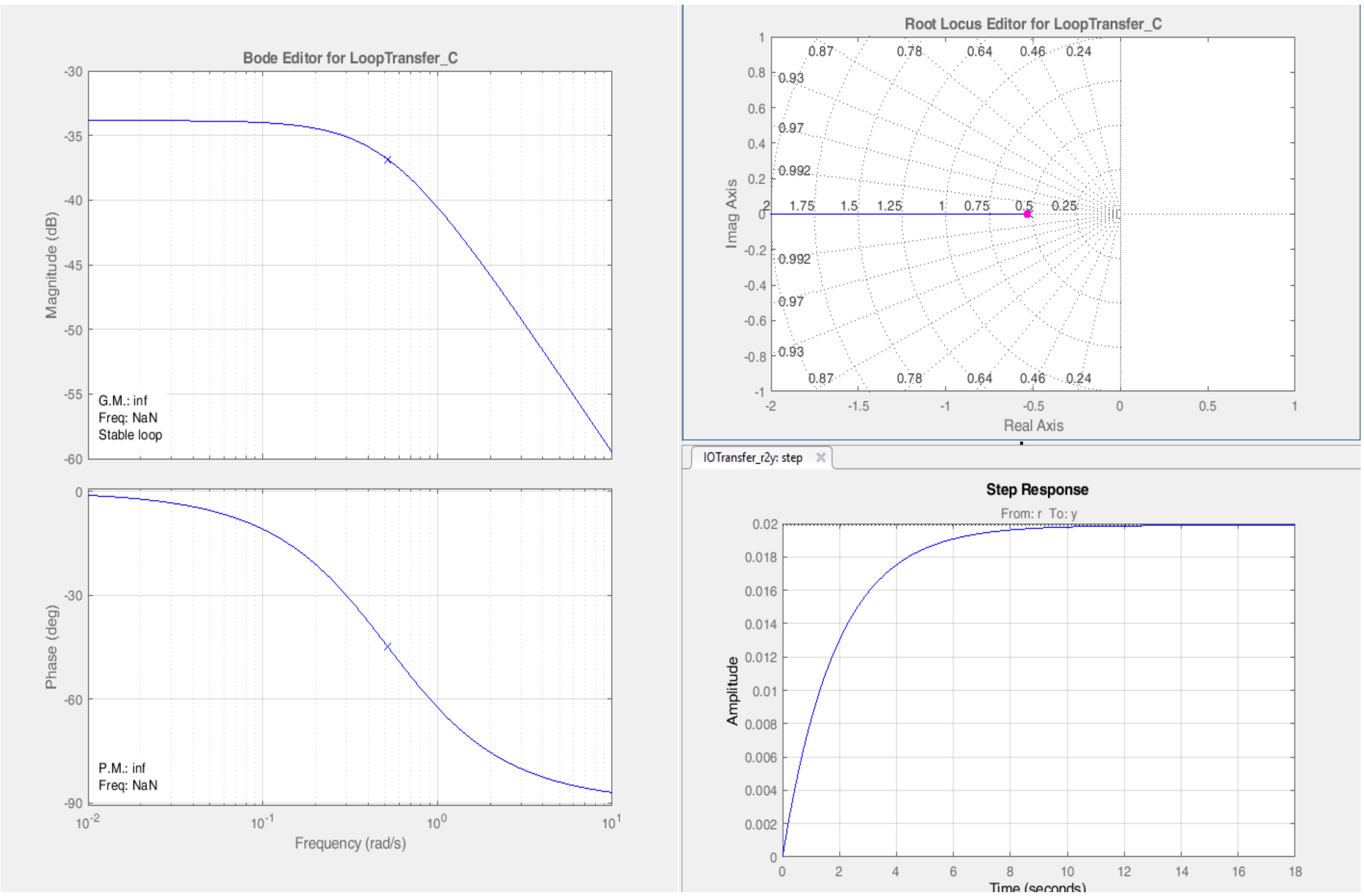


Figure 5: step plot of transfer function

Visible shown in Figure 6.In those options ,,design requirement'' is chosen and from that the ,,new'' option is also selected. When the new option is clicked with the left button of the mouse then a new window appears shown in Figure 7.In this window the controller specification is entered. For this case the corresponding parameter are mentioned in Table 2 below:

Table 2: PMSG controller parameter specification

Parameter name	Parameter value
Settling time	3 seconds
Rise time	5 seconds
Overshoot	10%

The input process when is completed then the **ok** button is pressed. After pressing the ok button the step plot will have a changed window. In that window there will be two regions. One region is white while the other will be shadowed shown in Figure 8.The zoom in option on the right side of the step plot shown in Figure 8 is used to make the white region larger. The step response curve lies in the pure white region. The main goal of the tuning is to bring the step response curve in this white region. Based on the controller specification requirement inputted in the controller designer options it creates these two regions. The white region means that the step response must be in this region.

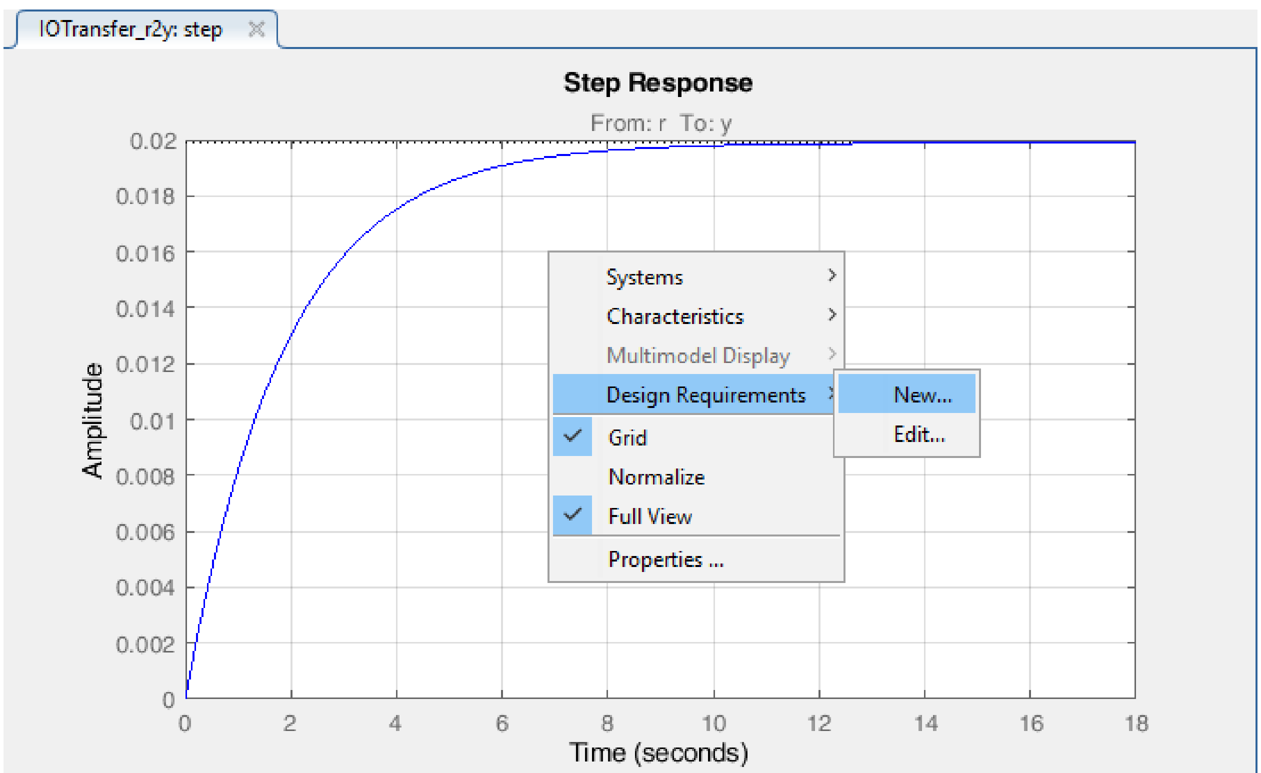


Figure 6: controller parameter specification input

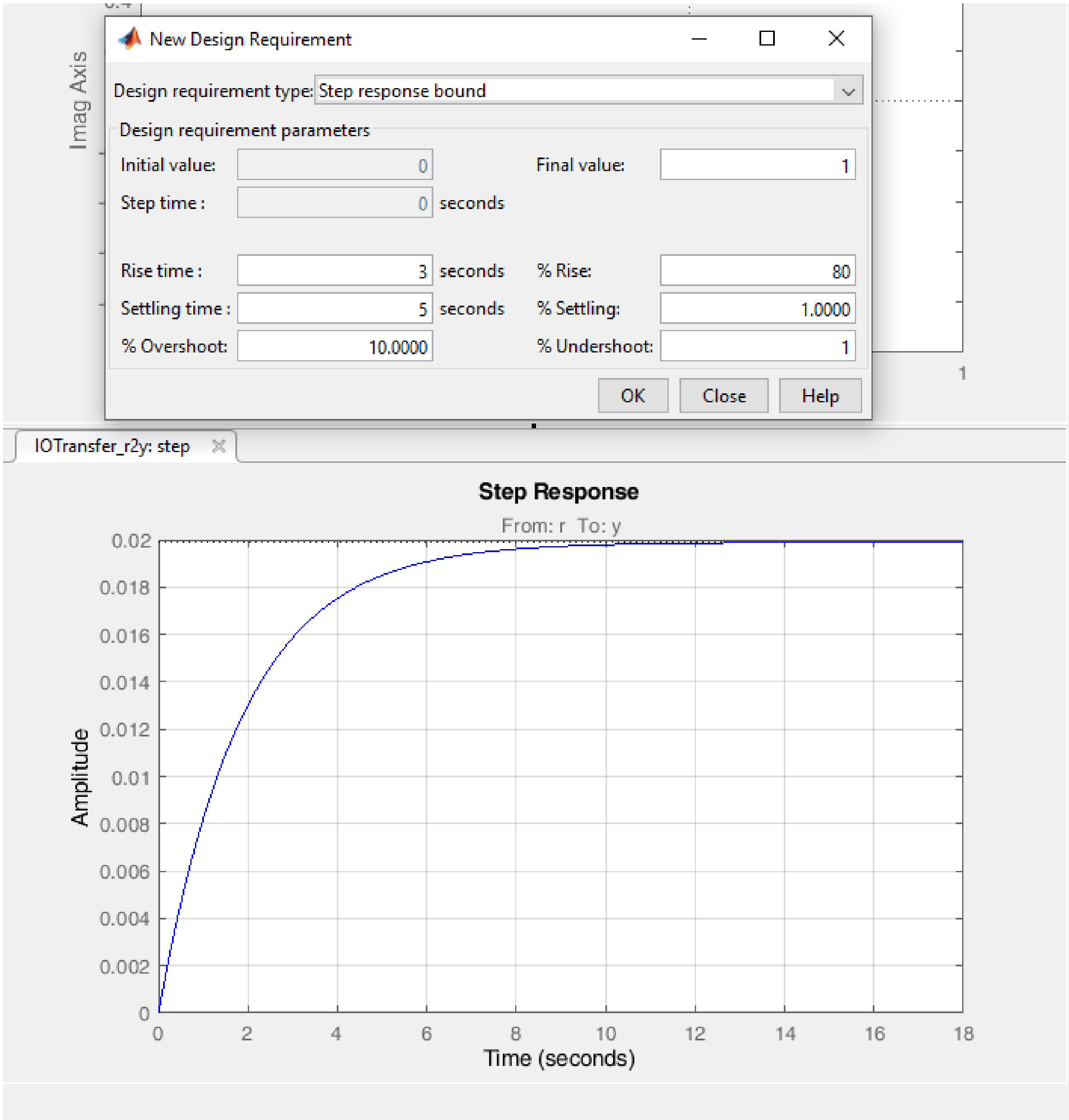


Figure 7: Design requirement input

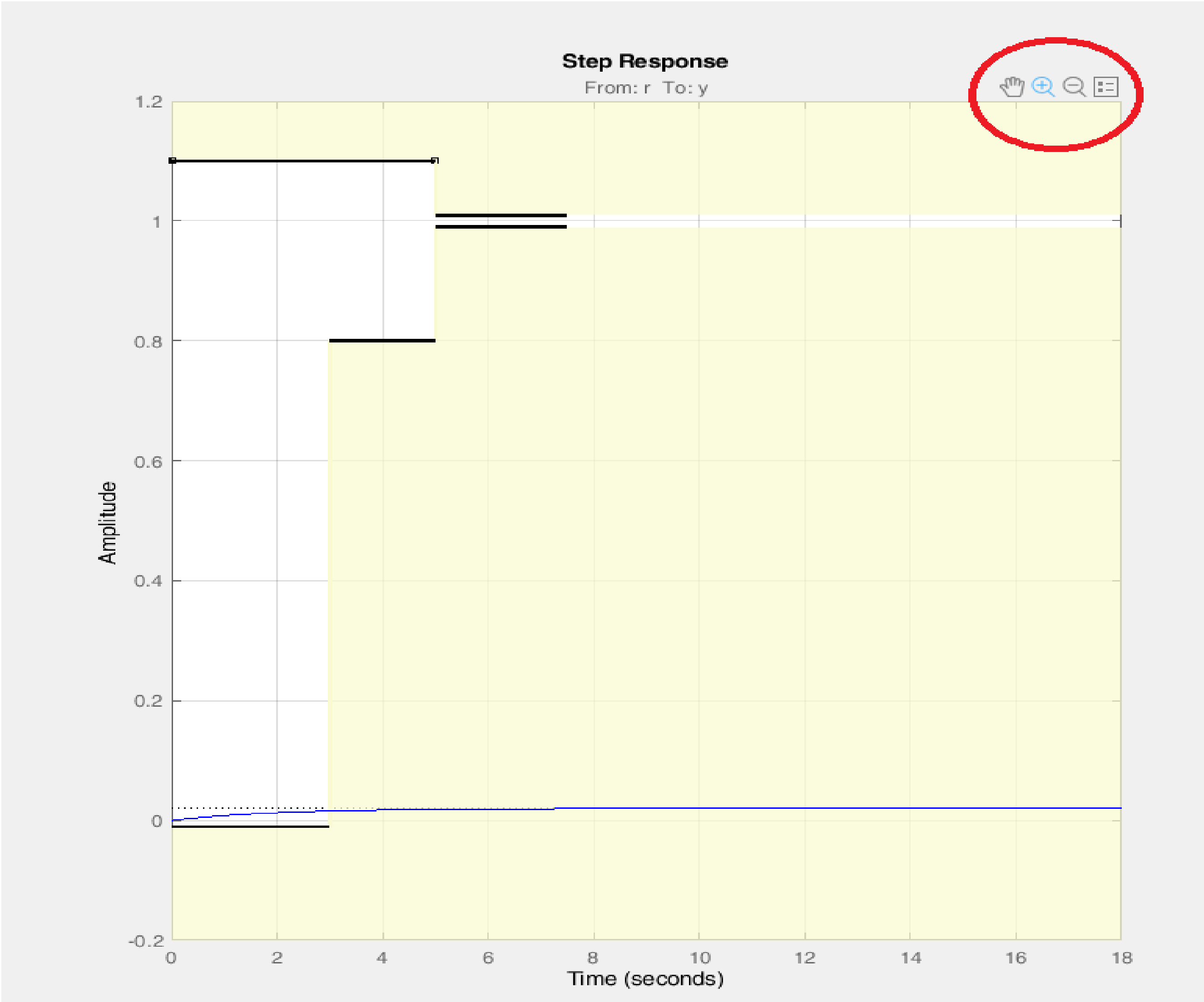


Figure 8: Regions of step plot after putting the parameter value

Step 4:

In this step the pid tuning option is brought to front. In the left side top the option tuning method option is clicked first, then under this option the PID Tuning option is clicked shown in Figure 9.After that a new window will be opened shown in Figure 9.It is seen in this figure that there are options to select between different controller types:P,PI,PID,PD. Among them PI Controller is selected.

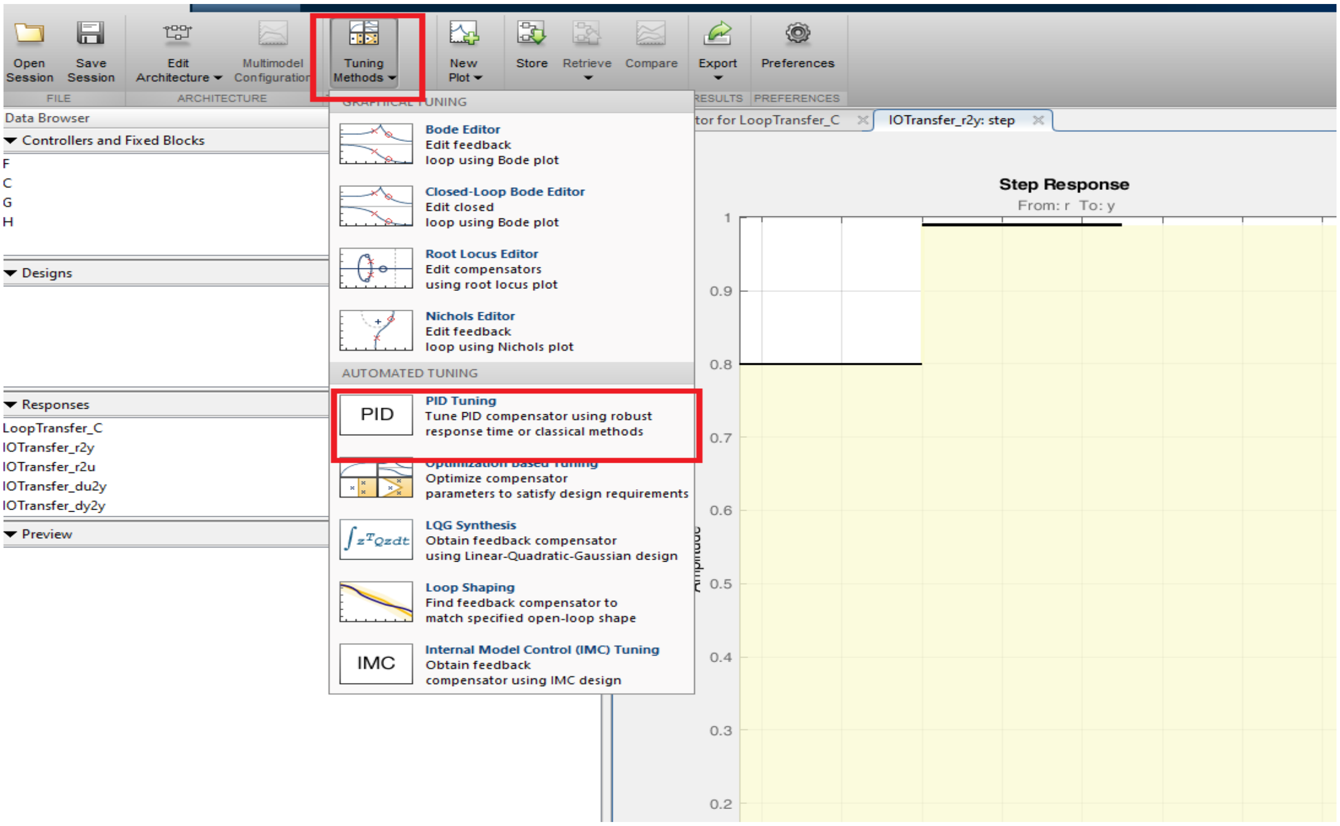


Figure 9: PID tuning option activating

Step 5:

In this step the controller tuning process is explained. In Figure 10 the pi controller tuning options are shown. There are two sections here. The first one is response time and the second one is transient behavior.

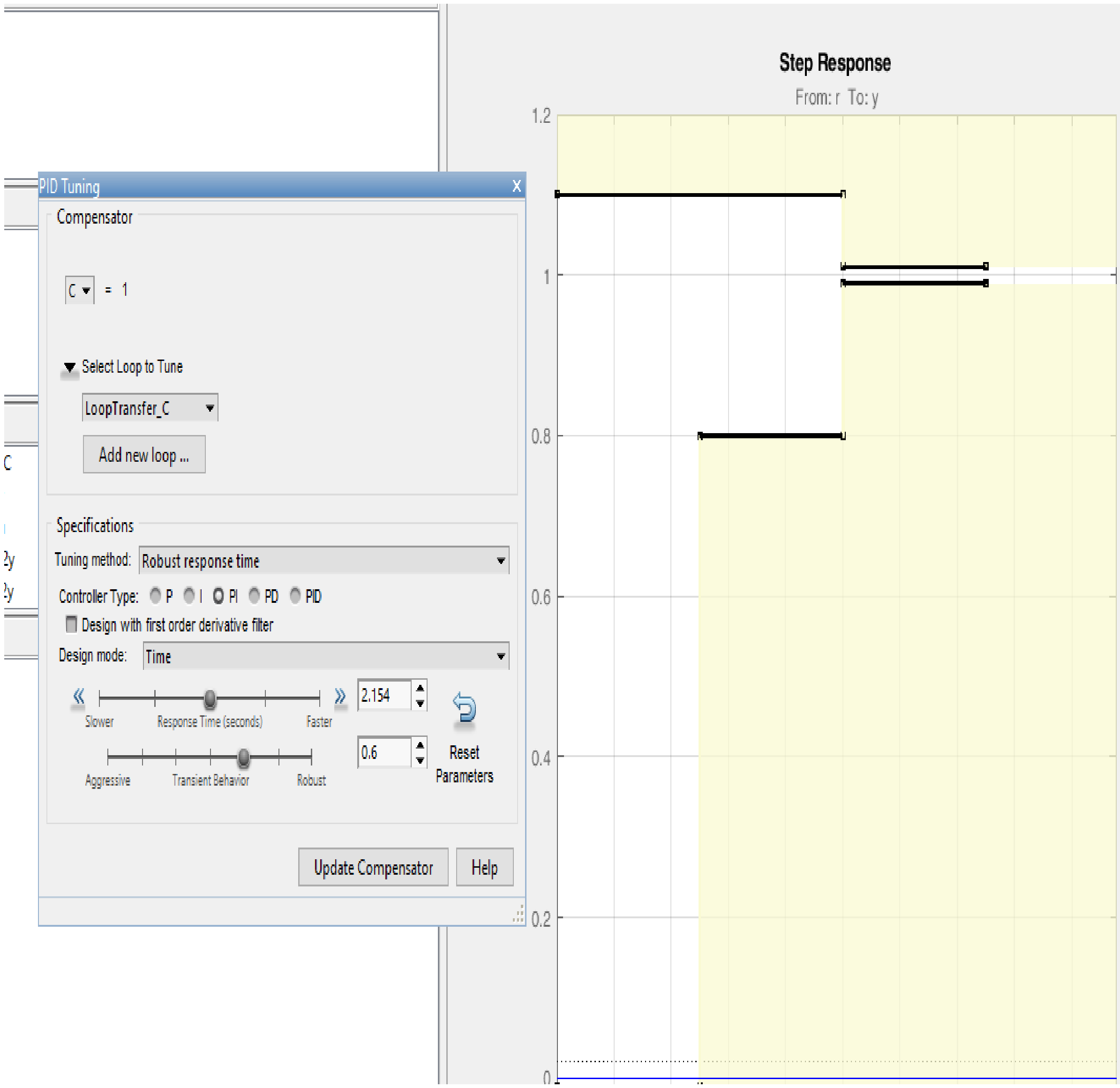


Figure 10: Controller tuning option

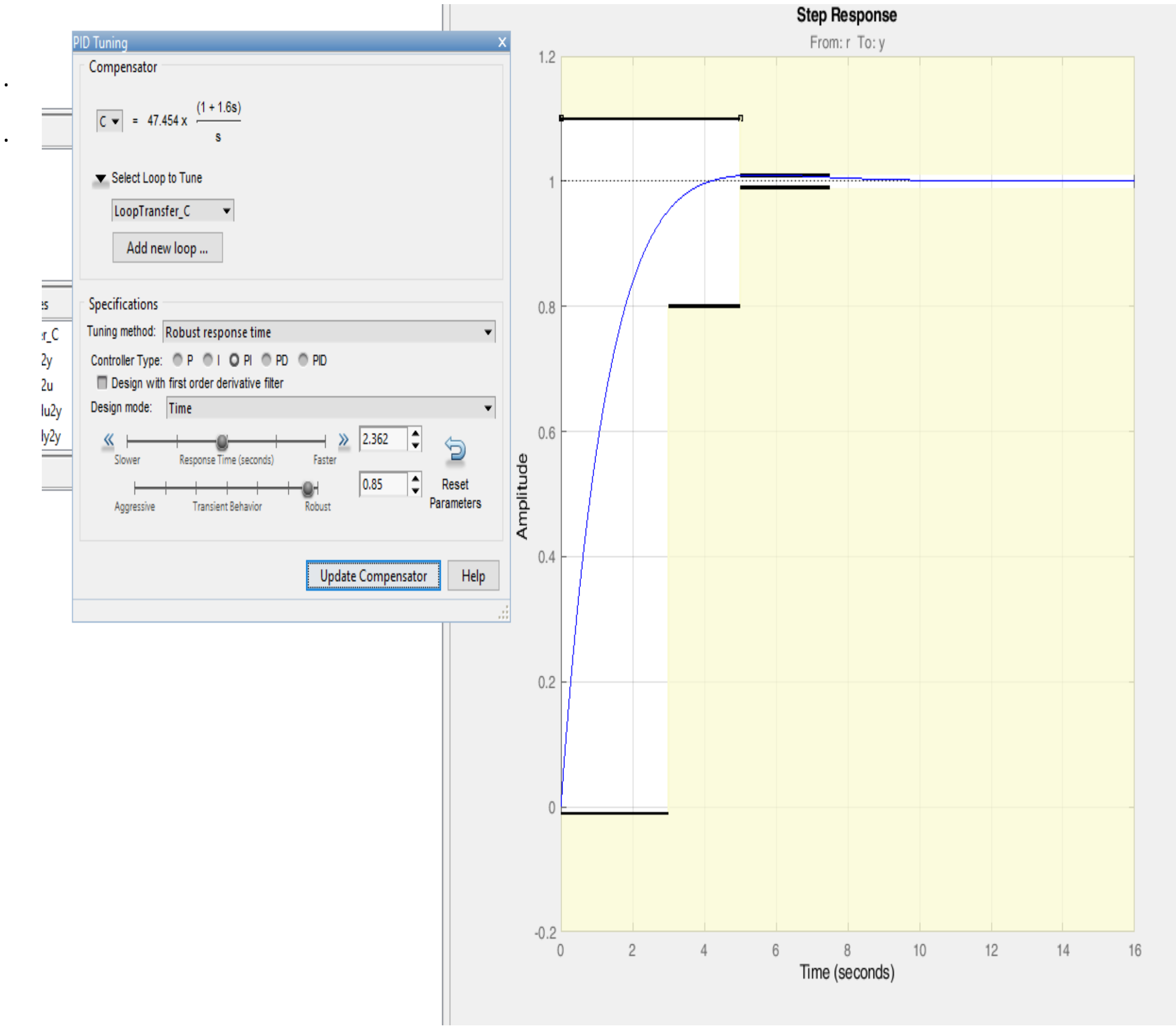


Figure 11: Controller calibration

When the response time is decreased then the proportional gain,Kp increases. It is a slider type button. This button is scrolled and the corresponding gain value has been observed until the step response curve comes to the white region. On the other hand if there is a steady state error then the transient behavior button is adjusted to make the steady state error to zero. The overshoot can be controlled by sliding this button.

In order to see the response after sliding the buttons, the update compensator button in the bottom is pressed.

Step 6:

When the controller is adjusted according to the requirement and put the step response in the white region, then the value of the compensator, C shown in Figure 11 is noted down and put the value in model to see the effect.

After adjusting the controllers the corresponding value of the proportional gain and the integral gain found are 47.45 and 75.2 respectively.

Once the desired characteristic is achieved then the controller tuning procedure is finished. The step response of the current controller with and without controller has been summarized below in the figure below.

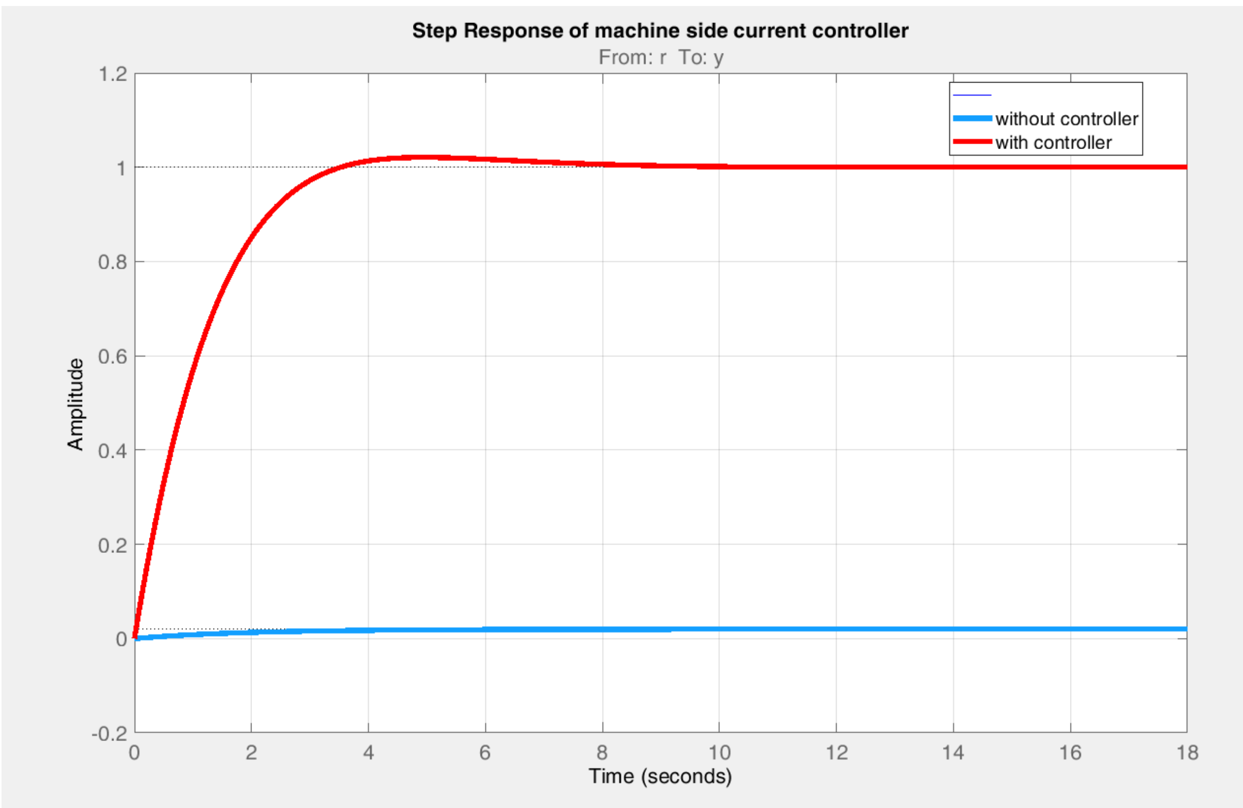


Figure 12: Step response of machine side current controller

Simulink block diagram of controller:

The Simulink block diagram of the generator controller has been shown below in **Error! Reference source not found.**.This is the internal architecture of the generator controller mentioned in Figure 2(magenta block on left side).In this diagram it is seen that the id and iq controllers are generating the reference voltage for the PWM generator.

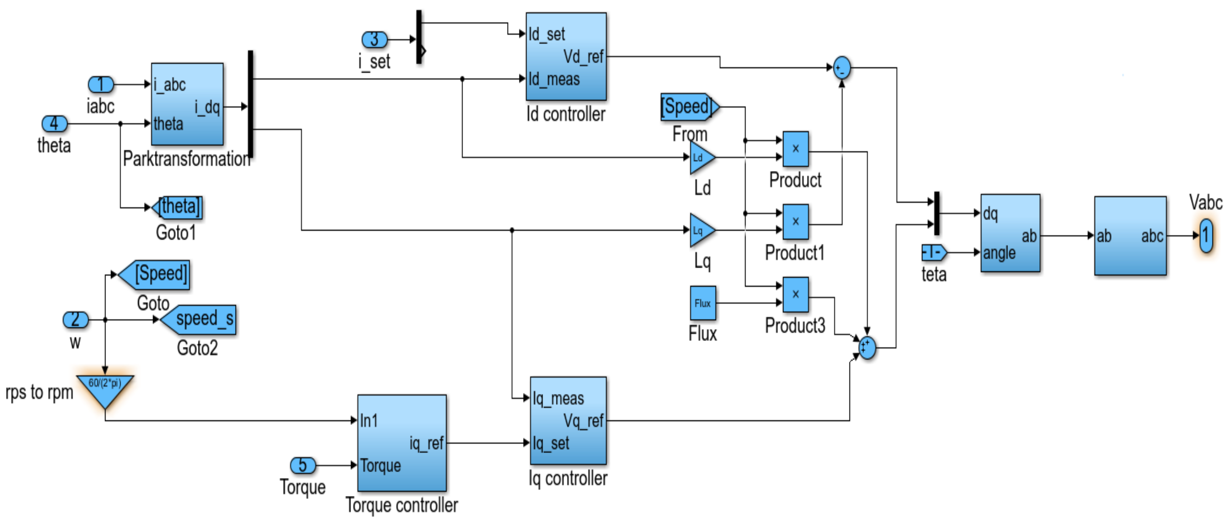


Figure 13: Internal architecture of the generator controller (shown in Figure 2)

The internal architecture of the iq current controller is shown in Figure 13.Only the iq controller has been discussed here since both the id an iq controllers are identical. Both have the same transfer function and for this reason the controller parameter of both systems are same. It is seen in Figure 14 that the reference value and measured value compared and the error is passing through a PI controller to stabilize the generator. The output of both the d and q axis current controller are reversely transformed from dq to abc shown in Figure 13 and this abc voltage reference is sent to the 3 level converter block shown in Figure 2.

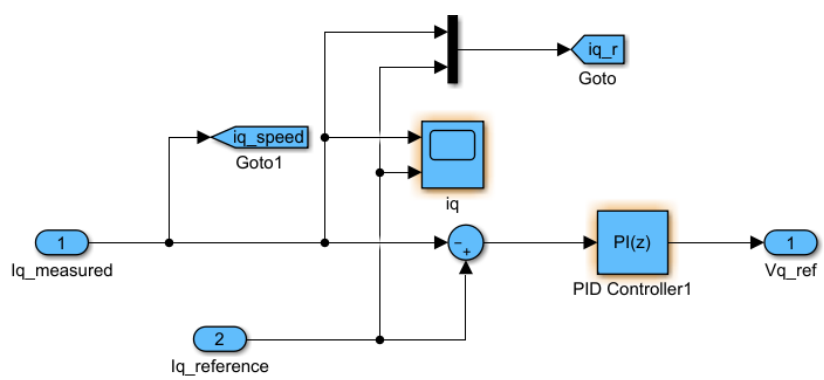


Figure 14: Internal architecture of iq controller (shown in Figure 13)

After generating the reference abc voltages and before the 3 level converter (shown in *Figure 2*) there is a gain block used. The purpose of using the gain block is to control the modulation index of PWM generator. The calculation of the gain parameter has been discussed below.

Gain block:

The purpose of using the gain block is to control the modulation index shown in Figure 1.After the PI controller block the reference voltages Vd and Vq are back transformed to Va,Vb,Vc three phase voltage signal. The output voltage goes to the three level converter for switching.

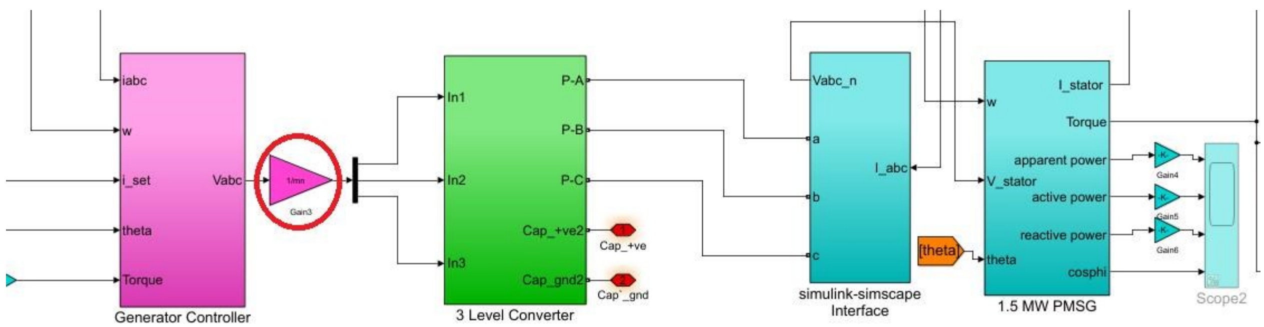


Figure 15: Gain block connection (marked red circle)

Calculation of gain value:

Firstly, the gain value of the block is set to 1, then the corresponding modulation index and charging current has been observed. The modulation index and charging current curve have been shown in Figure 15 and Figure 16 respectively. In Figure 15, it is seen that the reference sinusoidal signal is much larger than carrier wave. The modulation index is much higher than 1.It is calculated approximately as 6998.

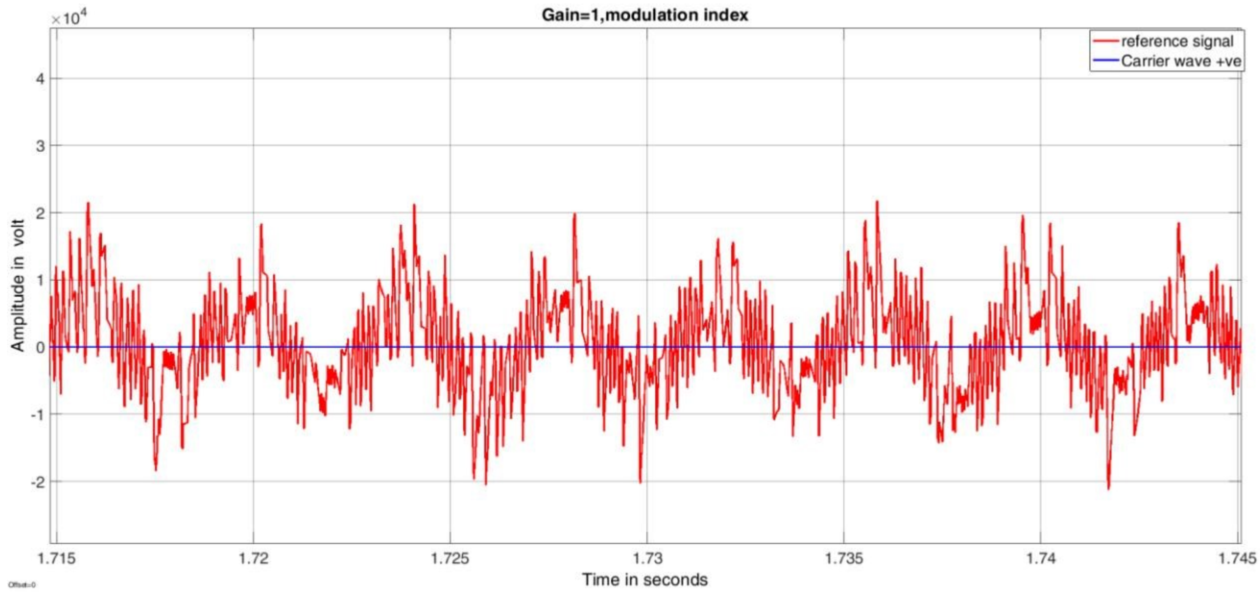


Figure 16: Modulation index visualization for gain=1

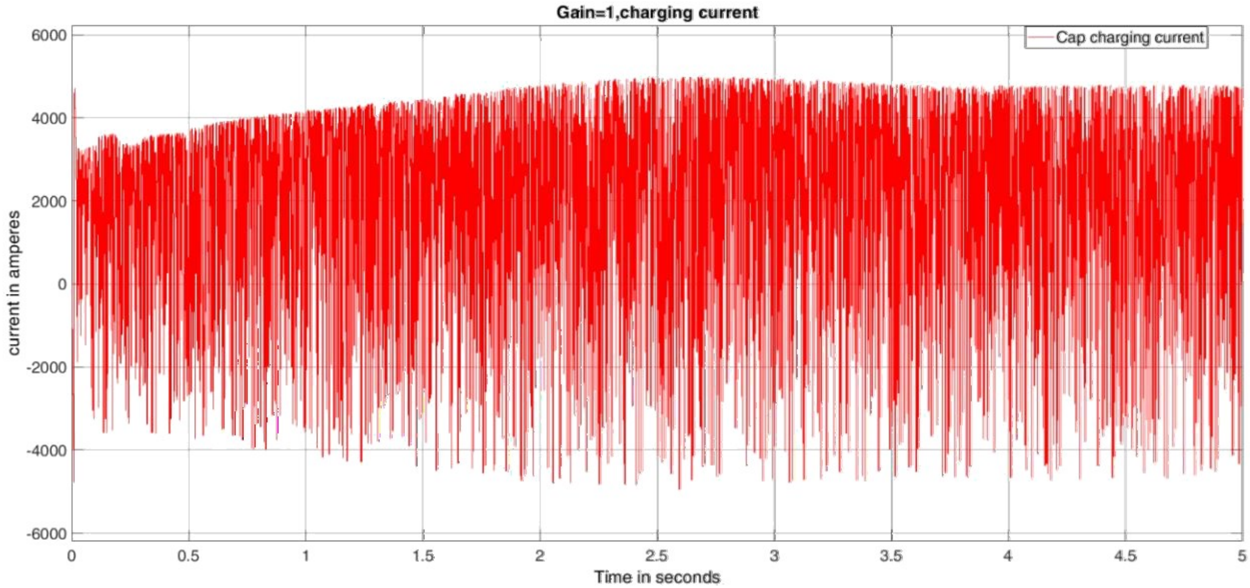


Figure 17: Capacitor charging current for gain=1

From Figure 3 it is seen that the value of the reference sinusoidal signal is approximately 2*10^4.The main target of this gain block is to make the MI=1 since in this value the harmonics in the output will be the least. So, the value of the gain block should be 1/2*10^4.In the next trial the gain block value has been set to 2*10^4 and the corresponding charging current and the MI is observed.

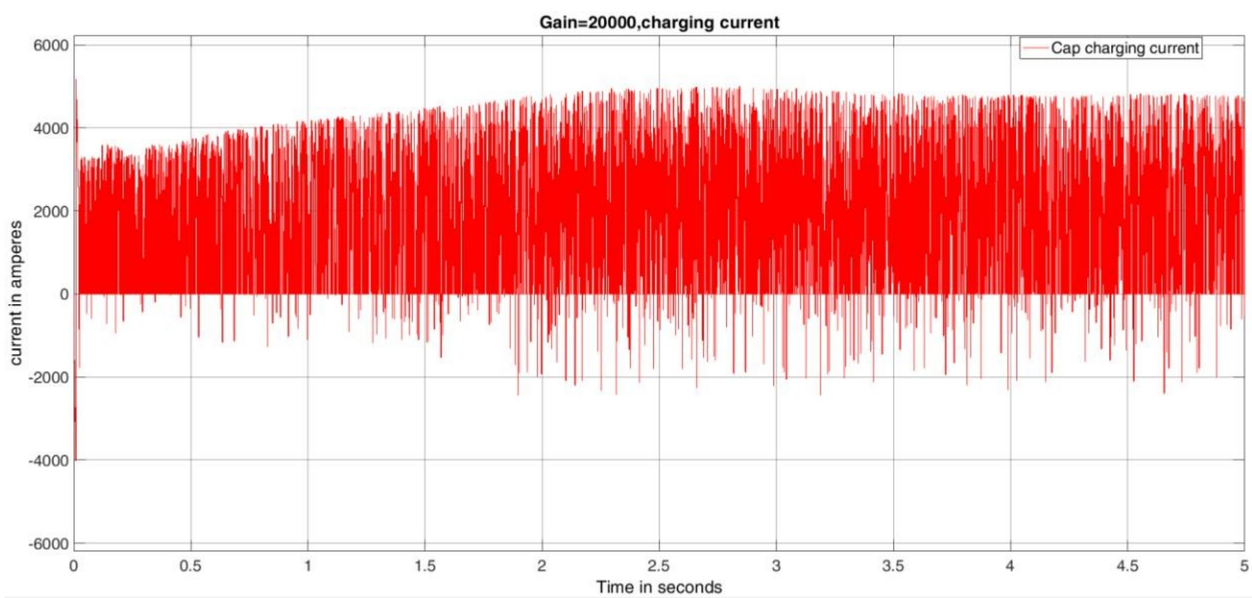


Figure 18: modulation index for gain=20000

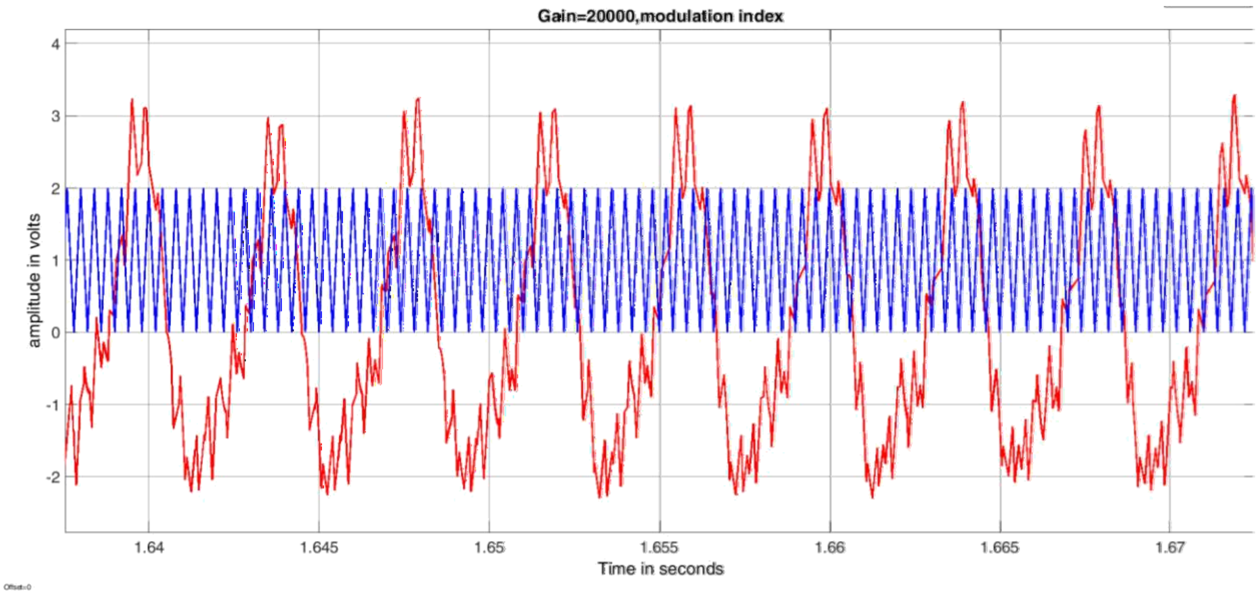


Figure 19: Capacitor charging current for gain=20000

It is seen from Figure 19 that the modulation index is 1.5 .The goal is not achieved yet. So, in the next trial the gain has been increased to 40000.

The corresponding charging current and the MI has been shown in Figure 20 and Figure 21 below.

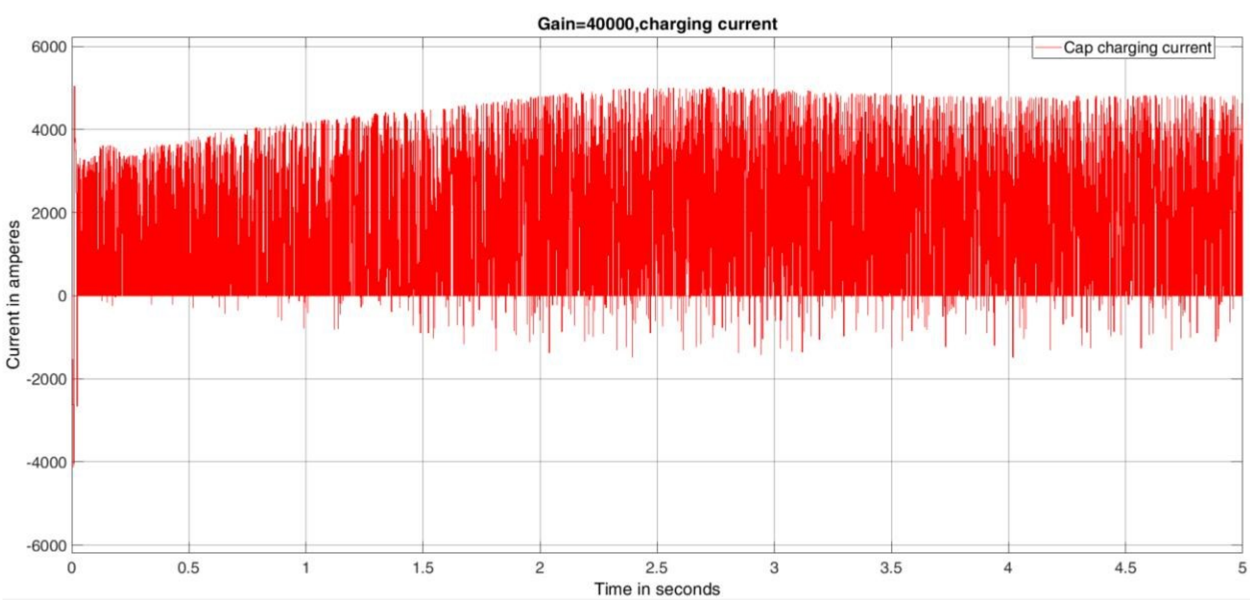


Figure 20: charging current for gain=40000

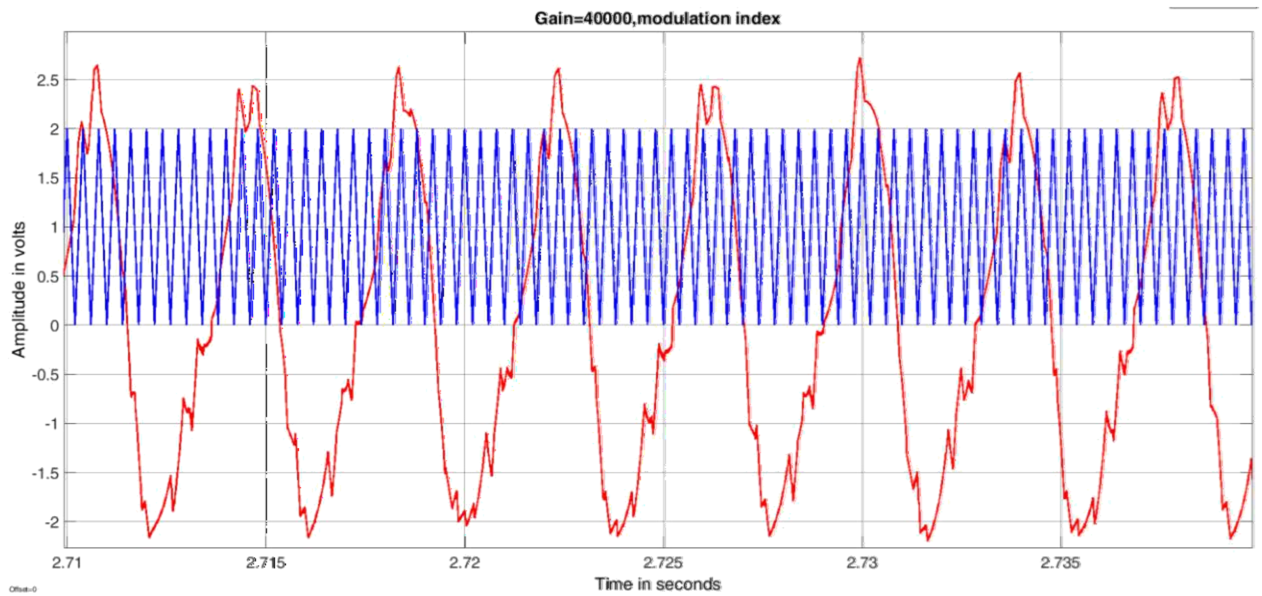


Figure 21: Modulation index for gain=40000

The charging current in Figure 22 shows better performance than Figure 20 since the negative portion of the charging current is less. On the other hand the modulation index in this case has been 1.25 .In this gain parameter the target has not been achieved. So, the gain is increased to 60000 in the next case.

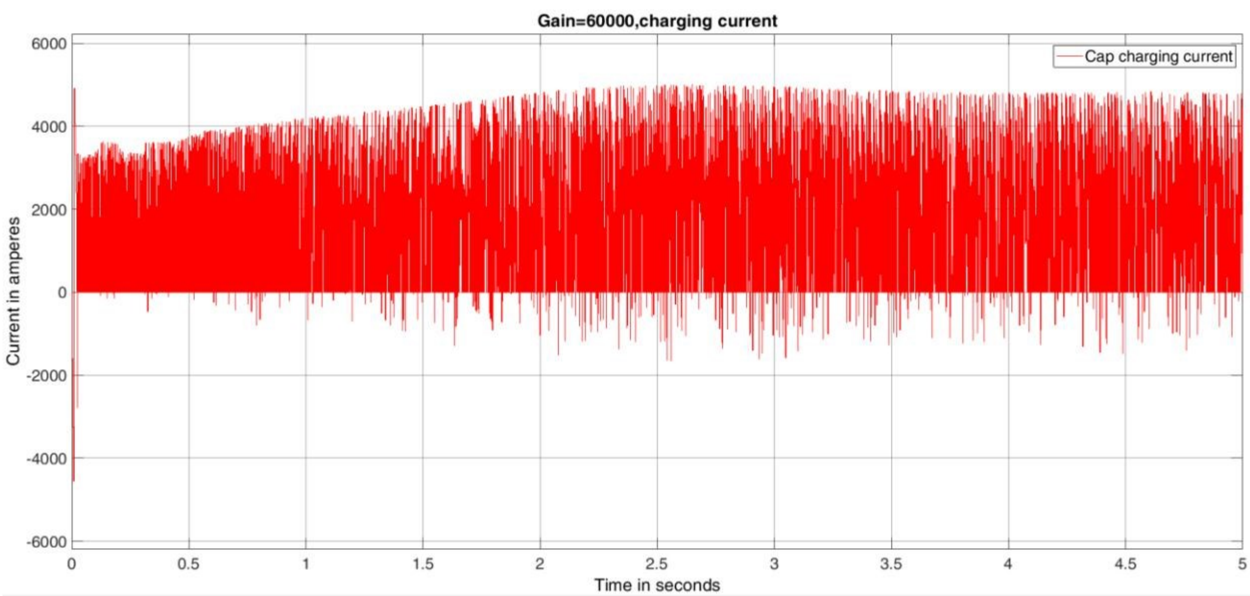


Figure 22: charging current for gain=60000

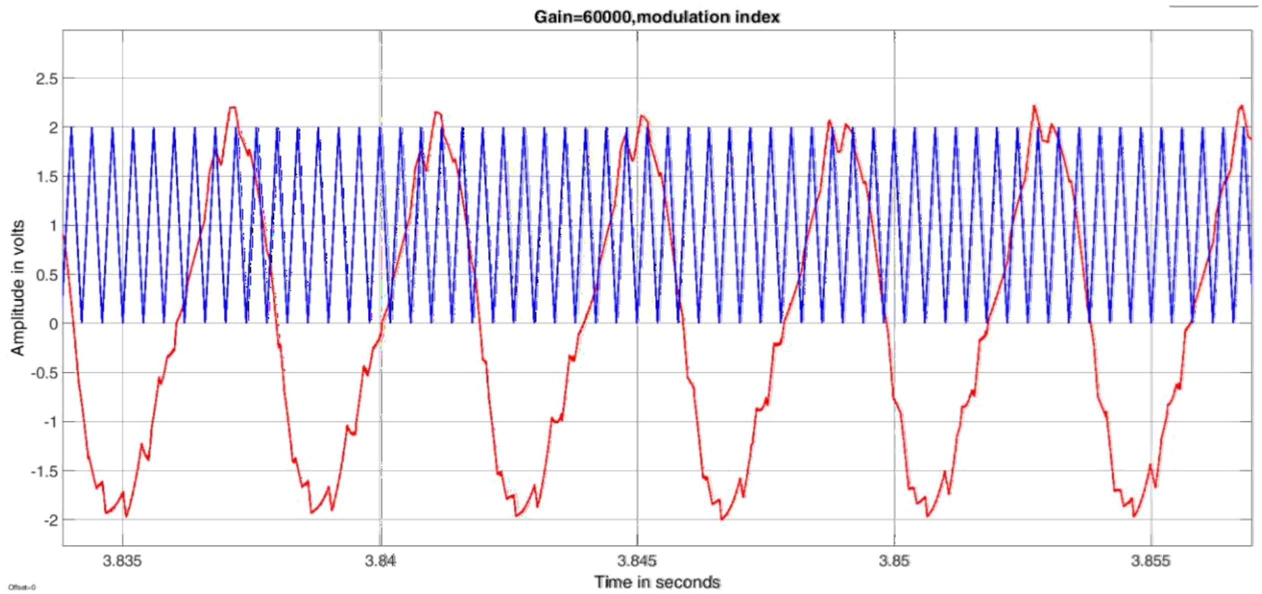


Figure 23: Modulation index for gain=60000

From Figure 23, it is seen that the charging current of the capacitor is not too much changed but the modulation index has been changed to 1.For better approximation of the modulation index the gain has been increased to 80000.

In Figure 24, the charging current for gain=80000 has been shown. It does not show too much charging current difference from the previous one (gain=60000) but the modulation index has been changed. The value falls below 1 and approximately reaches to 0.95.

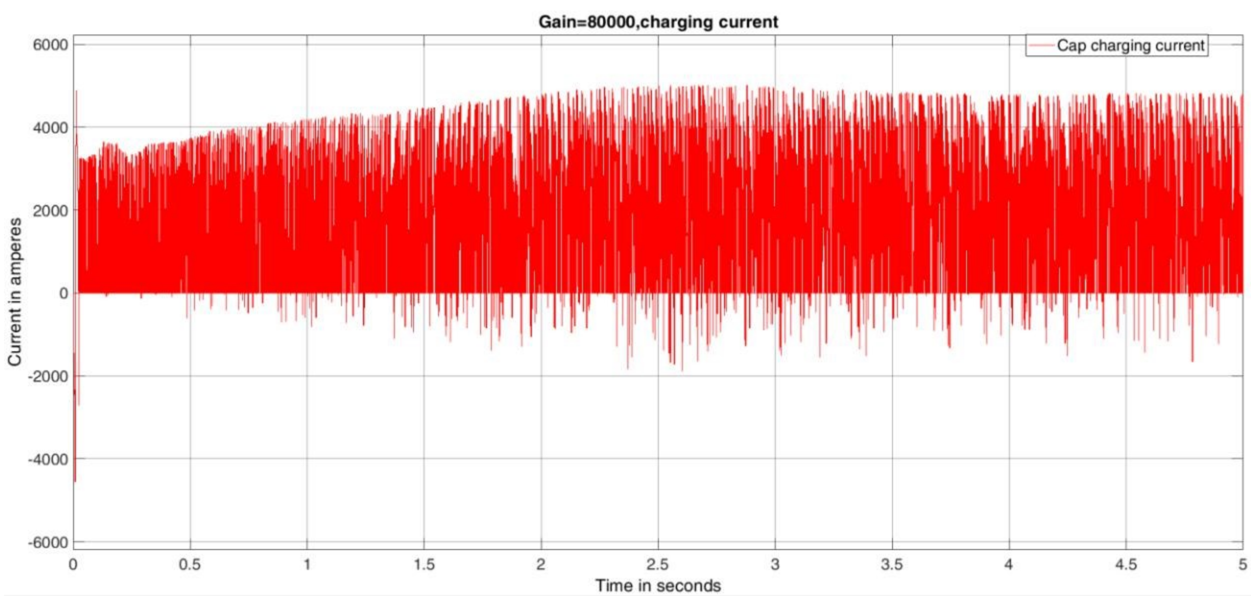


Figure 24: Charging current for gain=80000

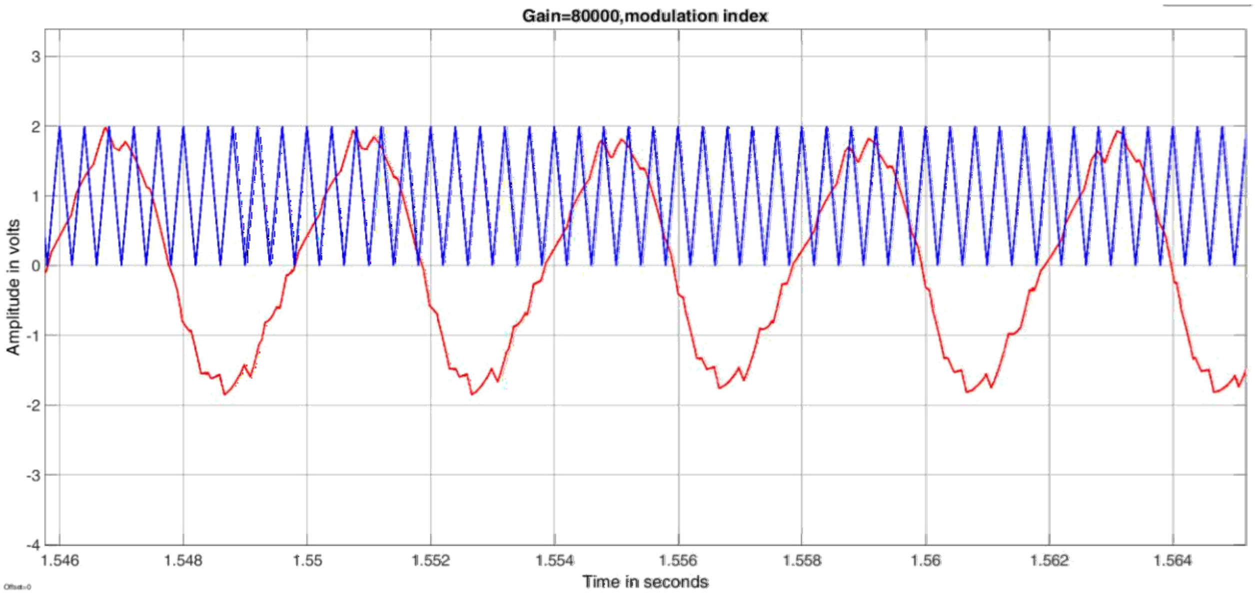


Figure 25: Modulation index for gain=80000

Hence, from the above explanation the summary of MI in different cases:

Table 3: Gain value vs modulation index

Gain value	Modulation index
1	6998
20000	1.5
40000	1.25
60000	1
80000	.95

Based on the modulation index summarized in table 1, it can be concluded that the gain parameter 60000 is the best choice. It is taken as the gain value in the following sections.

Simulation result:

In order to simulate the response of the id and iq current controllers the corresponding parameter have been mentioned in table 3 below:

Table 4: Simulation parameter for current control loop

Parameter name	Parameter value
Wind speed	12 m/s
Id reference	0
Proportional gain,Kp_pmsg	131
Integral gain,Ki_pmsg	248
Control mode	Id and iq control
Operating Mode	MPPT

N.B: iq reference current is taking the reference value from the torque loop.

For inner loop controller the id reference value was set at 0 since it is required to generate least amount of reactive power and maximum amount of real power. It is seen in Figure 26 below that within a few seconds the feedback value tracks the set value.

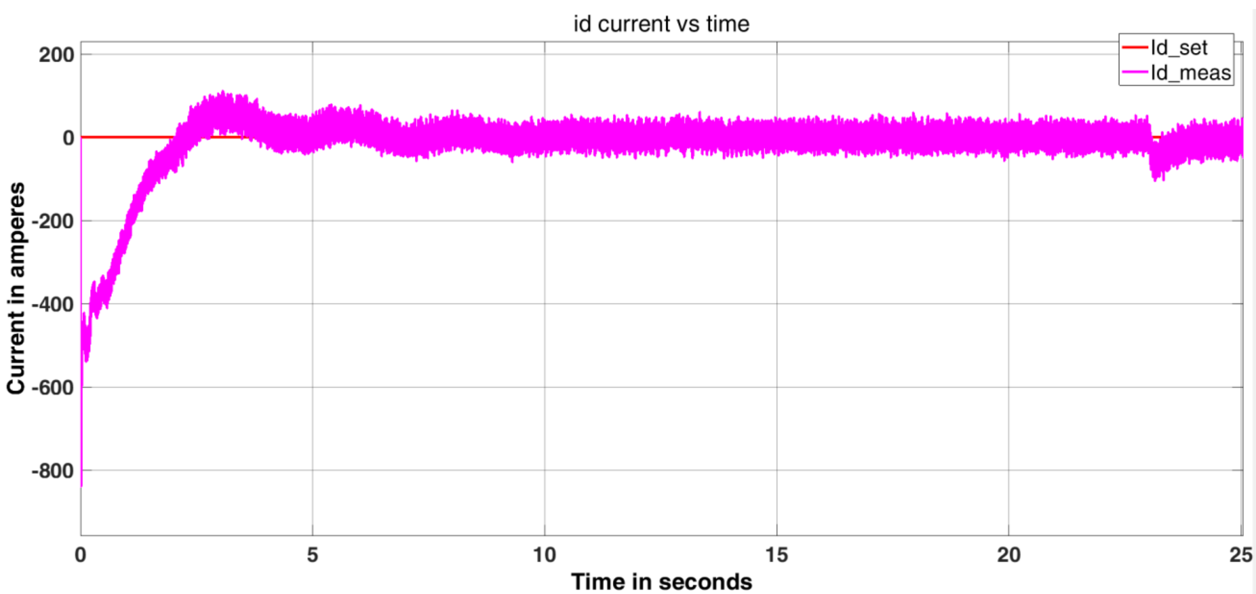


Figure 26: id current vs time of PMSG with controller

For iq controller the set value is coming from the outer control loop (torque control loop), the same tracking performance is also produced in the iq current control loop shown in Figure 27. The torque of the wind turbine passes through a transition period in the beginning. In this transition it takes some time to be stabilized. The relation between torque, inertia and angular acceleration is [13]-

$$T = \frac{1}{2} * M * R^2 * \alpha$$

Where,

M=mass of the rotor, R=radius of the rotor, α=angular acceleration,T=Torque.

At starting of the wind rotor the angular acceleration, α is nearly zero. So, the initial torque must act much higher on the inertia to accelerate it. Once it is accelerated then the torque requires less amount of effort on the inertia. This behavior is reflected on the iq characteristics curve in Figure 27.It is worth mentioning that the iq current controller is taking the reference from the torque control loop [13]

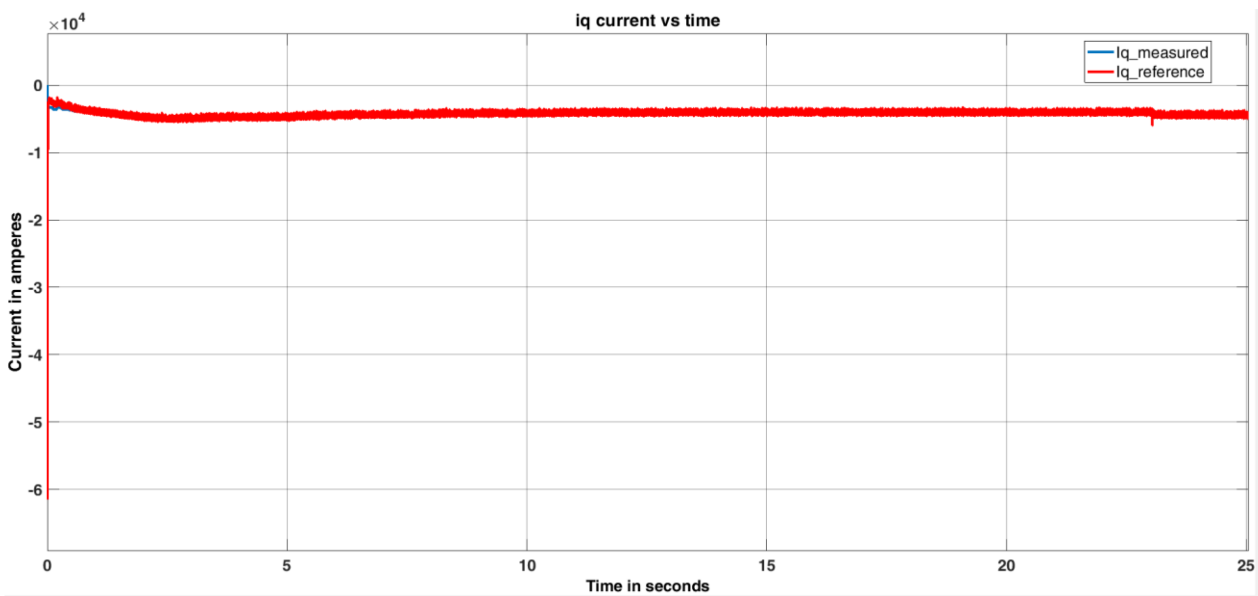


Figure 27: iq current vs time of PMSG with controller

1.2.2.2 Outer torque control loop

In this section, first of all the transfer function of the torque loop will be calculated, then step response would be taken to see the steady state response of the system. Next, the controller parameter would be realized from the step response output. After that the Simulink model of torque controller will be explained in details. Finally, the performance of the torque controller will be simulated.

Transfer function of the torque control loop:

Refer to Figure 4, it is seen that after the torque controller there are current controller PI values and the PMSG. After the PMSG the feedback torque is given to the torque controller. From Equation (3),

$$T_{em} = \frac{3}{2} * [(L_d - L_q) * I_d * I_q - \Phi_f * I_q]$$

Since $L_d = L_q$, therefore the first term of the equation above becomes zero. Hence, the equation becomes-

$$T_{em} = -\frac{3}{2} * \Phi_f * I_q$$

There are two stages (shown in Figure 28) through which the feedback torque is coming back to the reference for comparison. The first stage is through the PI controller, here the input is the Torque and output is the Vq voltage and next stage is through the PMSG, here the input is Vq and the output is the Iq current.

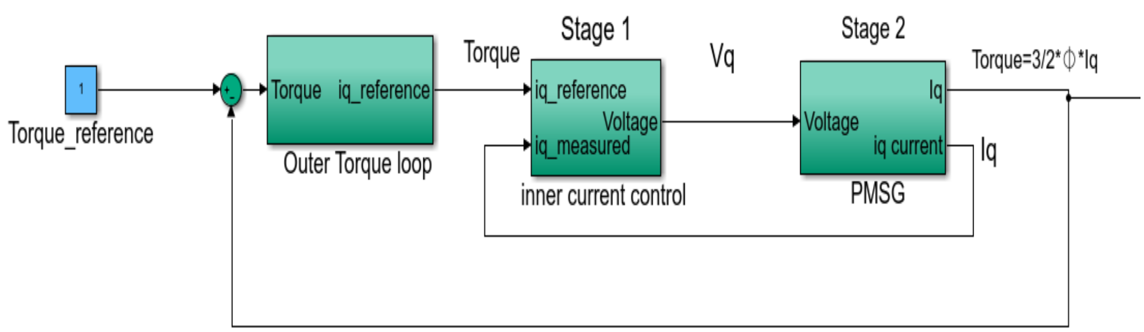


Figure 28: Torque loop stages

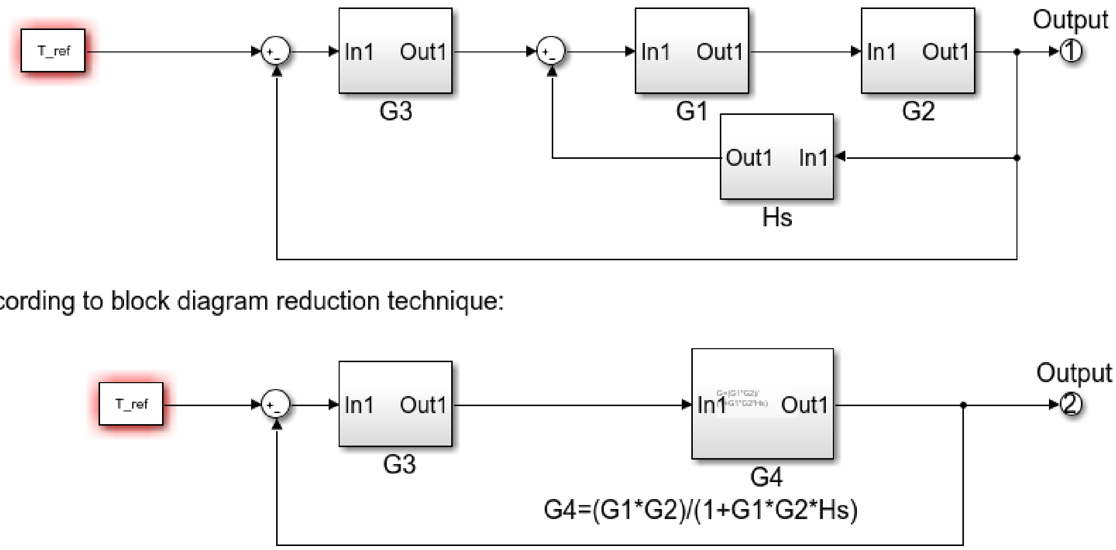


Figure 29: Block diagram reduction technique of torque controller

In the Figure 29 above the torque controller transfer function has been calculated using the block diagram reduction technique.G1 is the current controller calculated value and G2 is the transfer function of the PMSG,Hs is the feedback of the current loop. By using the reduction technique the upper block can be simplified to the block diagram shown in the bottom of Figure 29.

$$G1 = (Kp_i + \frac{Ki_i}{s})$$

$$G2 = \frac{1218}{(1.91 * s + 1) * 60000}$$

$$Hs = 1$$

Where,

G1=Current controller value of the current loop,

G2=transfer function of the PMSG,

G3=torque controller,

G4=Plant transfer function for the torque controller,

Hs=Feedback of the current loop.

Kp_i=Proportional gain of the current controller,

Ki_i=Integral gain of the current controller.

Therefore, the complete plant transfer function for the torque loop is:

$$G4 = \frac{1218 * (Kp_i * s + Ki_i)}{s * (1.91 * s + 1) * 60000 + 1218 * (Kp_i * s + Ki_i)}$$

Torque controller tuning for PMSG:

Step 1:

From mathematical calculation the transfer function of the current controller loop is:

$$tf\_torque = \frac{1218 * (Kp_i * s + Ki_i)}{s * (1.91 * s + 1) * 60000 + 1218 * (Kp_i * s + Ki_i)}$$

Where,

Kpi=proportional gain of the current controller of pmsg.

Ki_i =integral gain of the current controller of pmsg.

Sample matlab code to formulate the transfer function in the command window:

```
R=0.000821;
Ld=0.001575;
Lq=0.001575;
%PI controller gain of pmsg controller
kp_pmsg=47.5;
ki_pmsg=75.2;
%transfer function of pmsg
num_pmsg=[1];
den_pmsg=[Ld R]*mn;
tf_pmsg=tf(num_pmsg,den_pmsg);

%% Torque controller parameter
kp_torque=18.19;
ki_torque=2165.6;

%transfer function of the current controller of pmsg
num_pi_pmsg=[kp_pmsg ki_pmsg];
den_pi_pmsg=[1 0];
tf_pi_pmsg=tf(num_pi_pmsg,den_pi_pmsg);

%total open loop transfer function of torque loop
tf_torque=feedback(tf_pmsg*tf_pi_pmsg,1);
```

Output:

tf_torque =

47.5 s + 75.2

94.5 s^2 + 96.76 s + 75.2

Step 2:

The transfer function is run in the matlab command window.Next,a matlab command to call the sisotool is executed in the command window.

Sisotool(tf_torque)

Step 3:

When the command is executed then a step plot will be appeared in a new window shown in Figure 30.In that window the bode plot and root locus plot will also appear along with it but only the step plot is considered. The mouse cursor is put in step plot and the right button is clicked, a new option will be

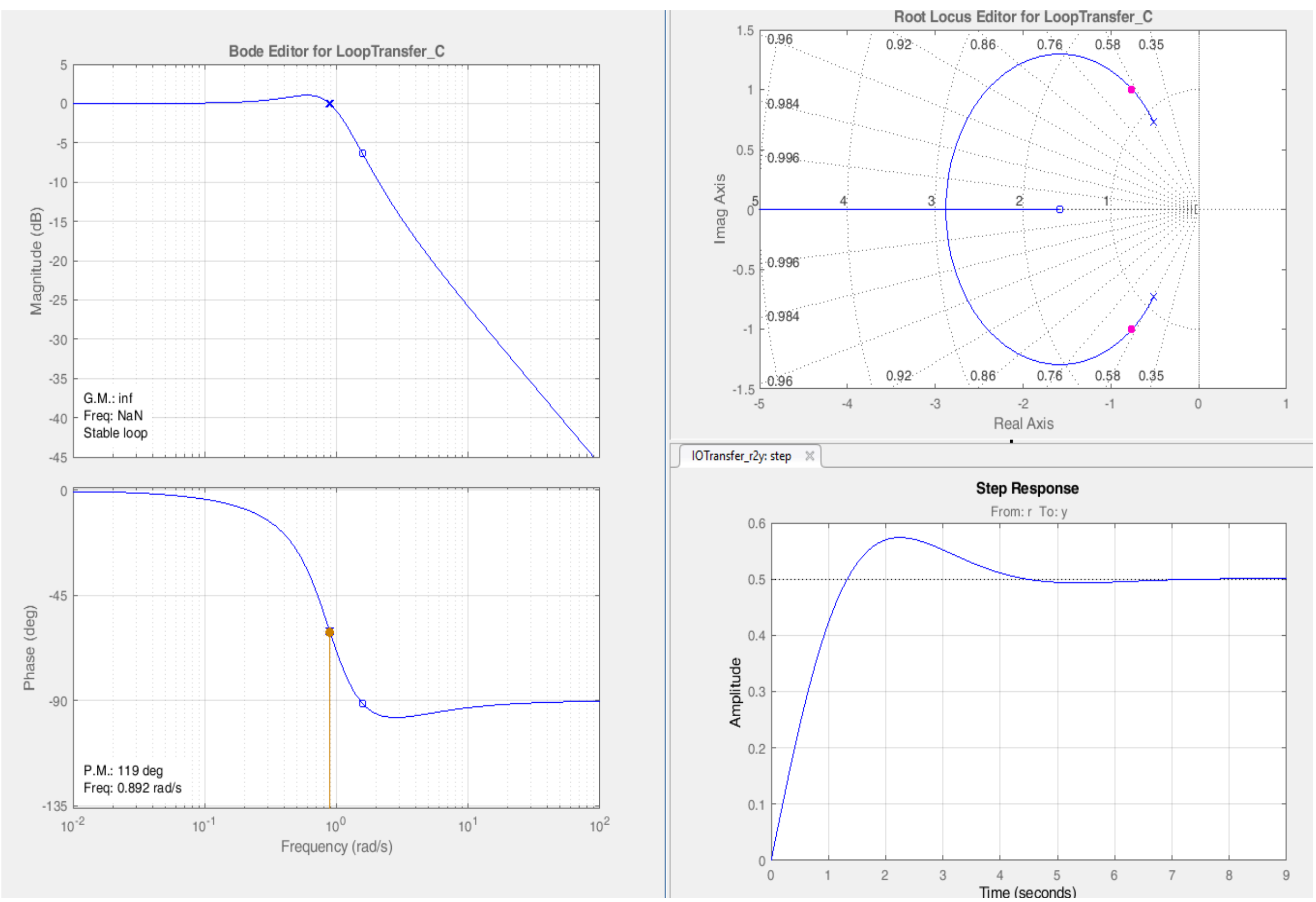


Figure 30: step plot of transfer function

Visible shown in Figure 31.In those options ,,design requirement'' is chosen and from that the ,,new'' option is also selected. When the new option is clicked with the left button of the mouse then a new window appears shown in Figure 7.In this window the controller specification is entered. For this case the corresponding parameter are mentioned in Table 5 below:

Table 5: PMSG torque controller parameter specification

Parameter name	Parameter value
Settling time	0.5 seconds
Rise time	1 seconds
Overshoot	10%

The input process when is completed then the **ok** button is pressed. After pressing the ok button the step plot will have a changed window. In that window there will be two regions. One region is white while the other will be shadowed shown in Figure 8.The zoom in option on the right side of the step plot shown in Figure 8 is used to make the white region larger. The step response curve lies in the pure white region. The main goal of the tuning is to bring the step response curve in this white region. Based on the controller specification requirement inputted in the controller designer options it creates these two regions. The white region means that the step response must be in this region.

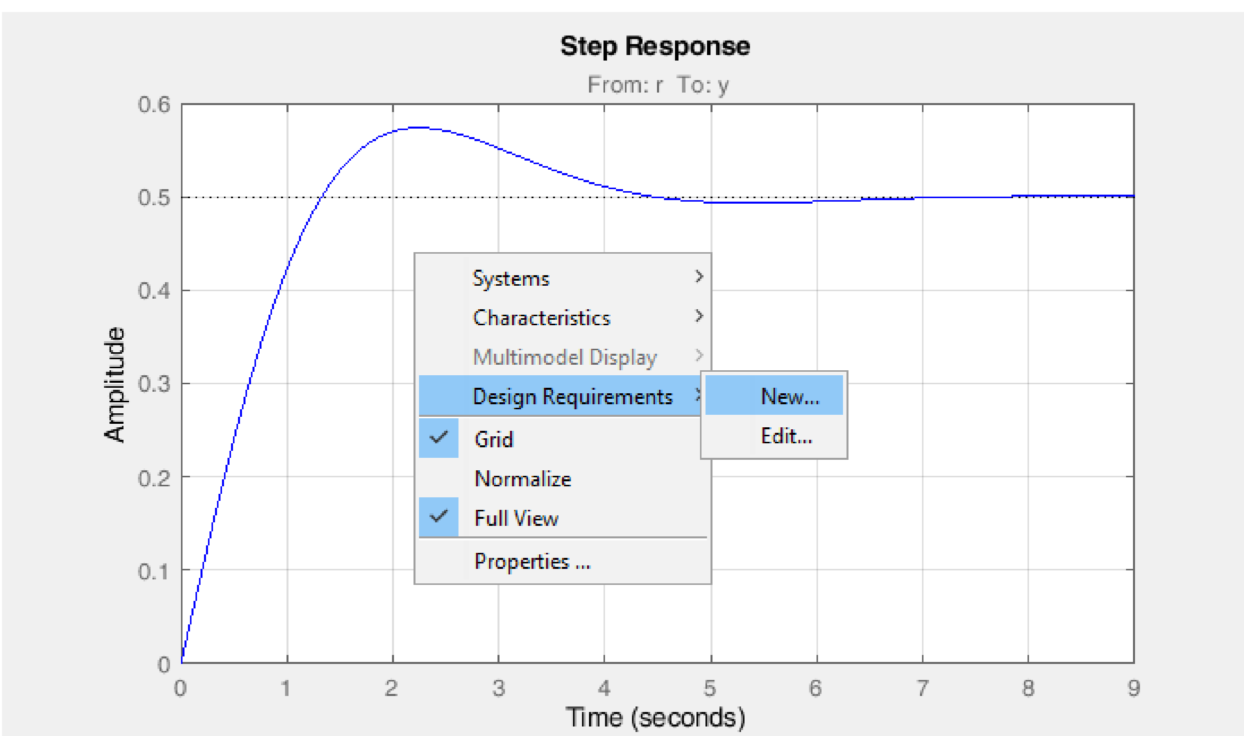


Figure 31: controller parameter specification input

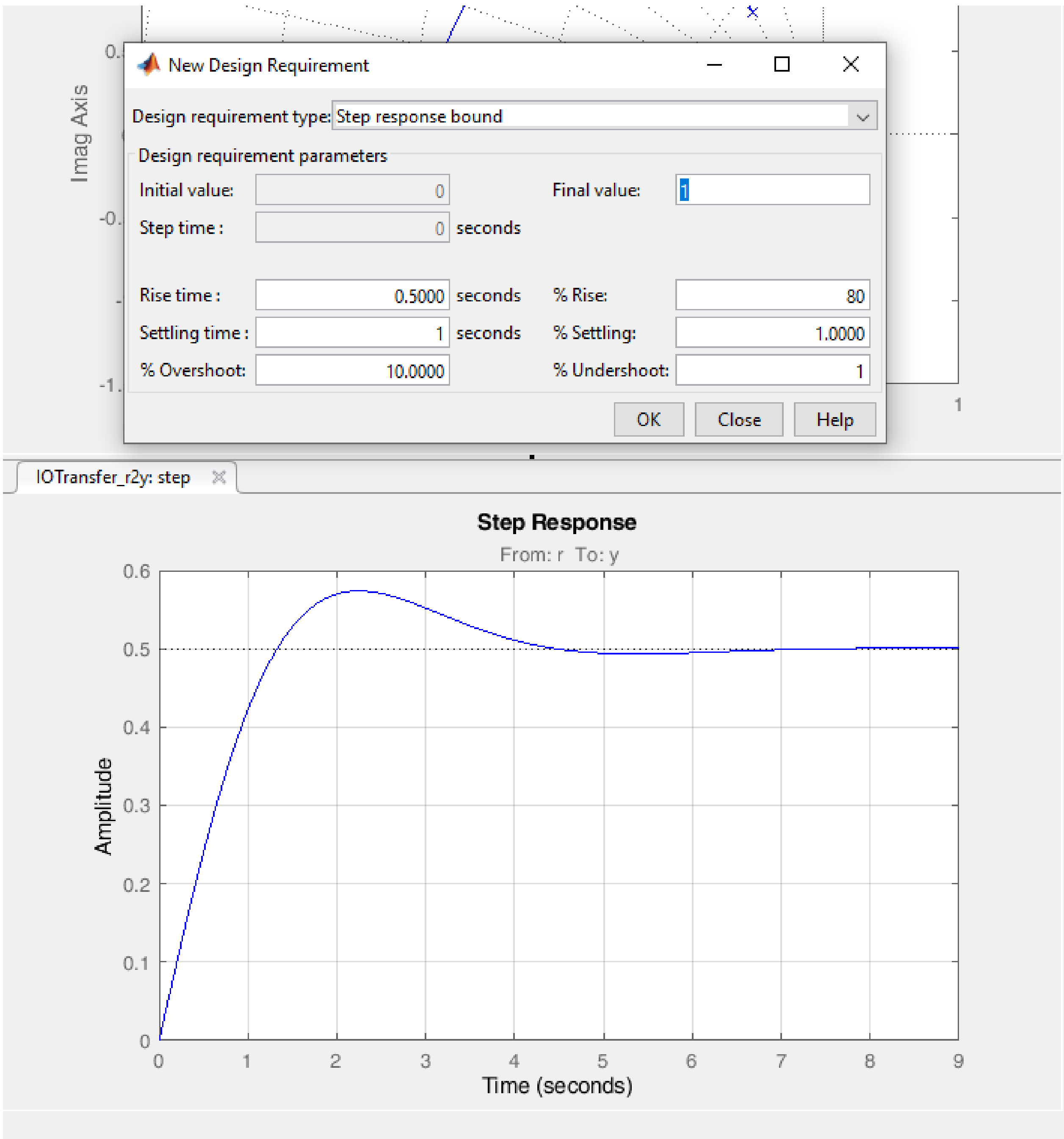


Figure 32: Design requirement input

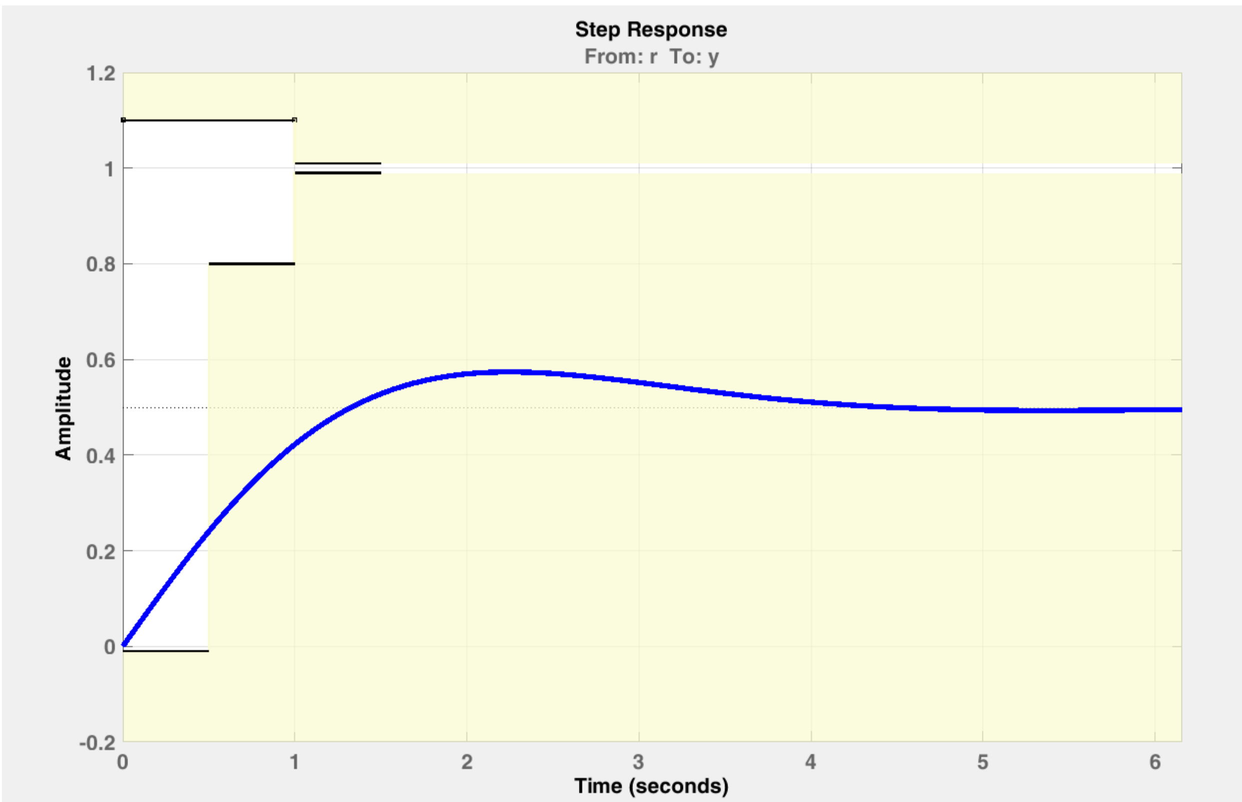


Figure 33: Regions of step plot after putting the parameter value

Step 4:

In this step the pid tuning option is brought to front. In the left side top the option tuning method option is clicked first, then under this option the PID Tuning option is clicked shown in Figure 34.After that a new window will be opened shown inFigure 35.It is seen in this figure that there are options to select between different controller types:P,PI,PID,PD. Among them PI Controller is selected.

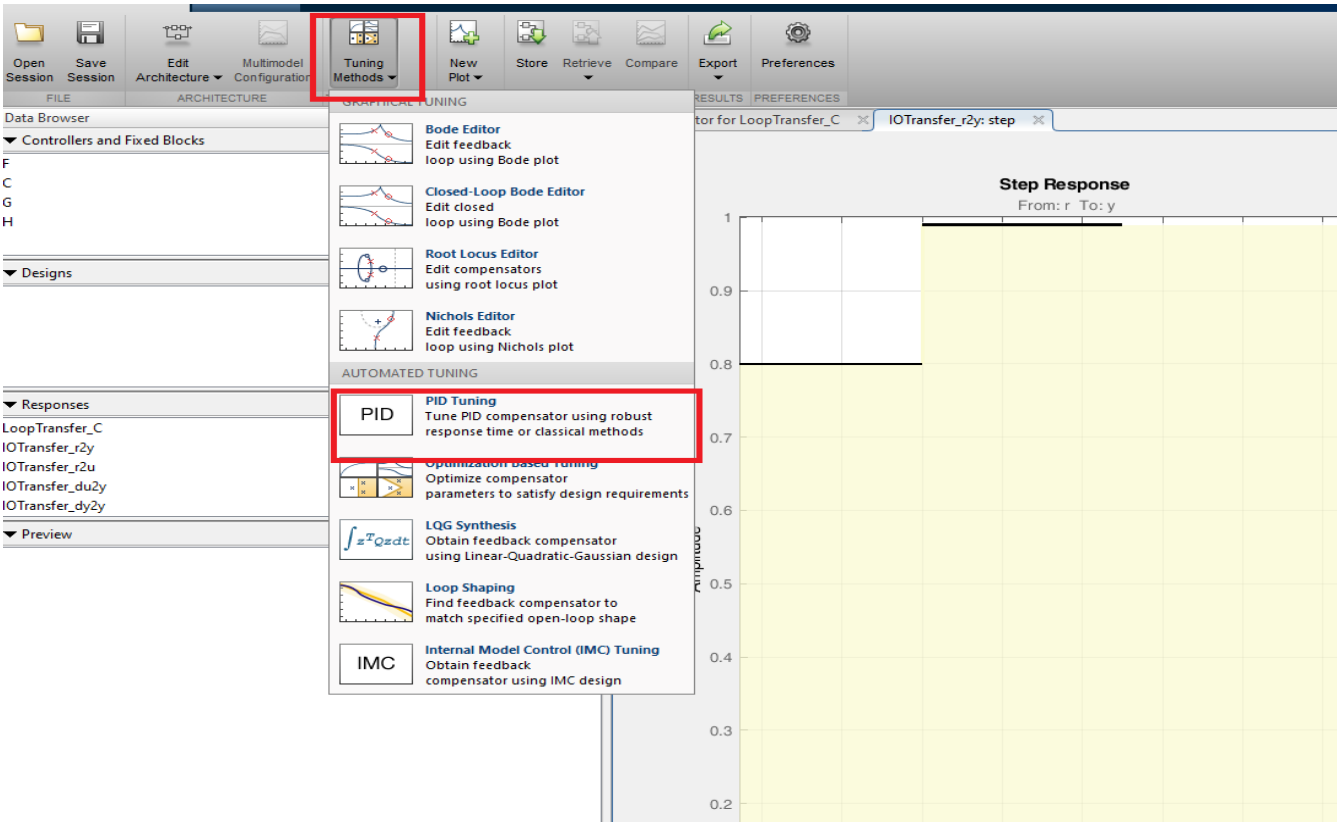


Figure 34: PID tuning option activating

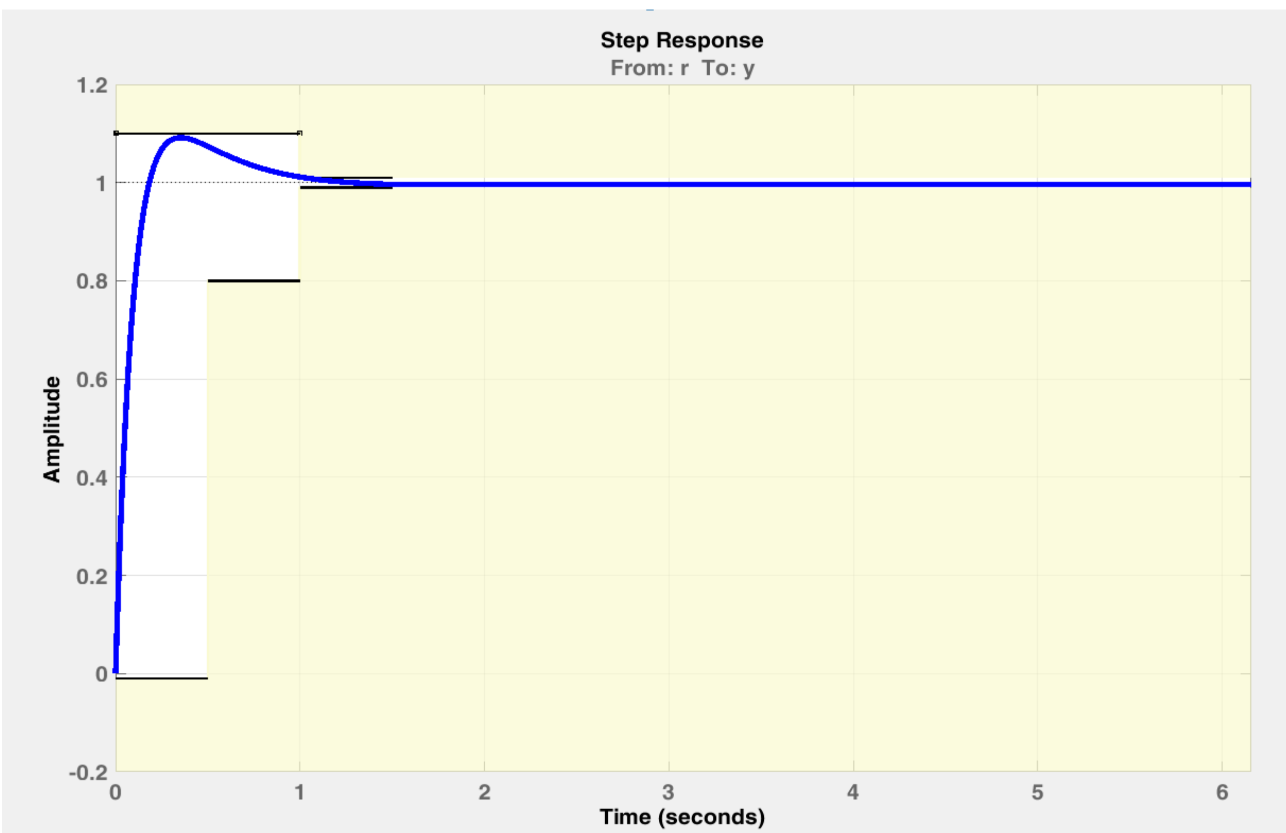


Figure 35: Controller tuning option

Step 5:

In this step the controller tuning process is explained. In Figure 36 the pi controller tuning options are shown. There are two sections here. The first one is response time and the second one is transient behavior.

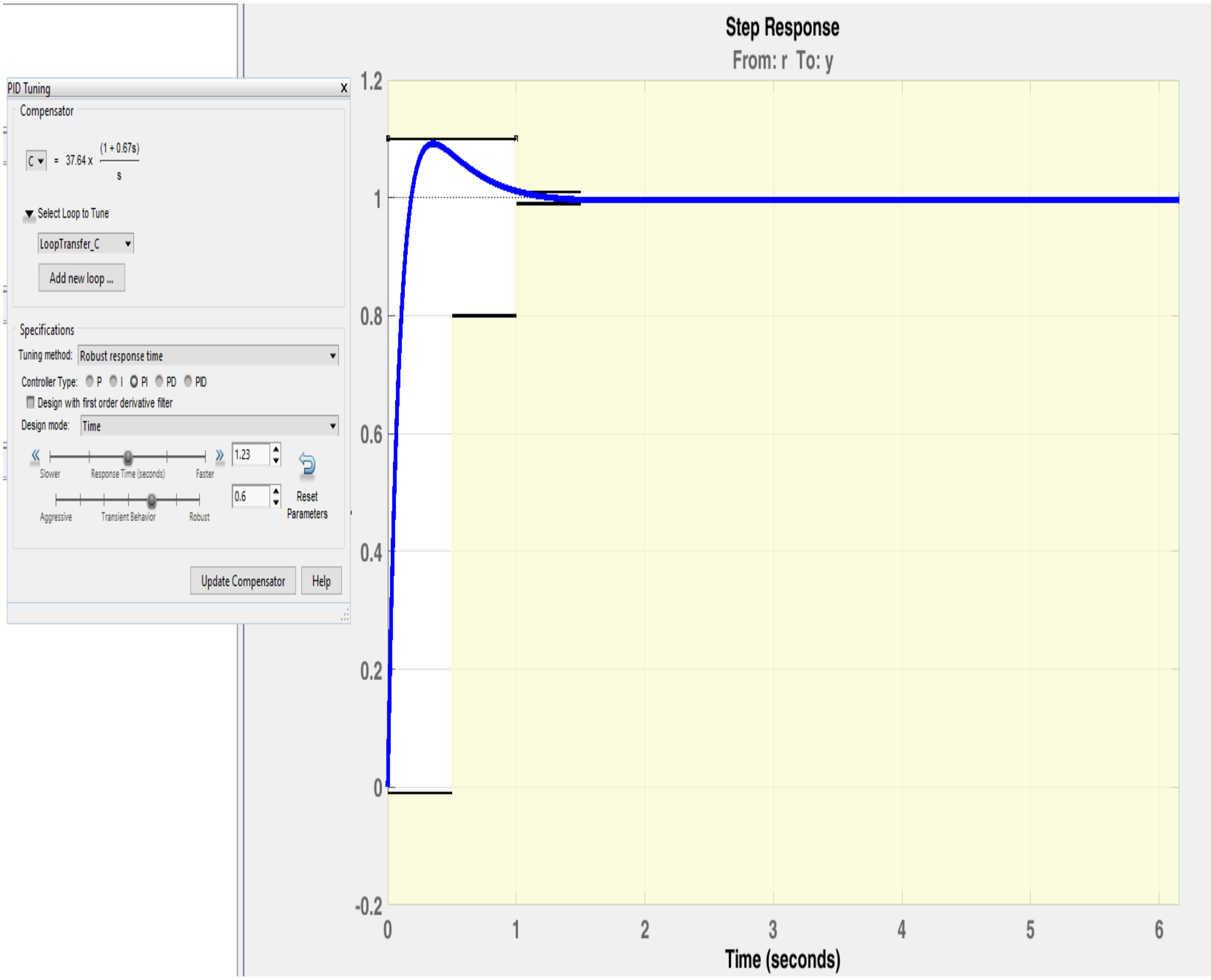


Figure 36: Controller calibration

When the response time is decreased then the proportional gain, Kp increases. It is a slider type button. This button is scrolled and the corresponding gain value has been observed until the step response curve comes to the white region. On the other hand if there is a steady state error then the transient behavior button is adjusted to make the steady state error to zero. The overshoot can be controlled by sliding this button.

In order to see the response after sliding the buttons, the update compensator button in the bottom is pressed.

Step 6:

When the controller is adjusted according to the requirement and put the step response in the white region, then the value of the compensator, C shown in Figure 37 is noted down and put the value in model to see the effect.

After adjusting the controllers the corresponding value of the proportional gain and the integral gain found are 25.21 and 37.64 respectively.

Once the desired characteristic is achieved then the controller tuning procedure is finished. The step response of the torque control loop with and without controller is shown below in the figure.

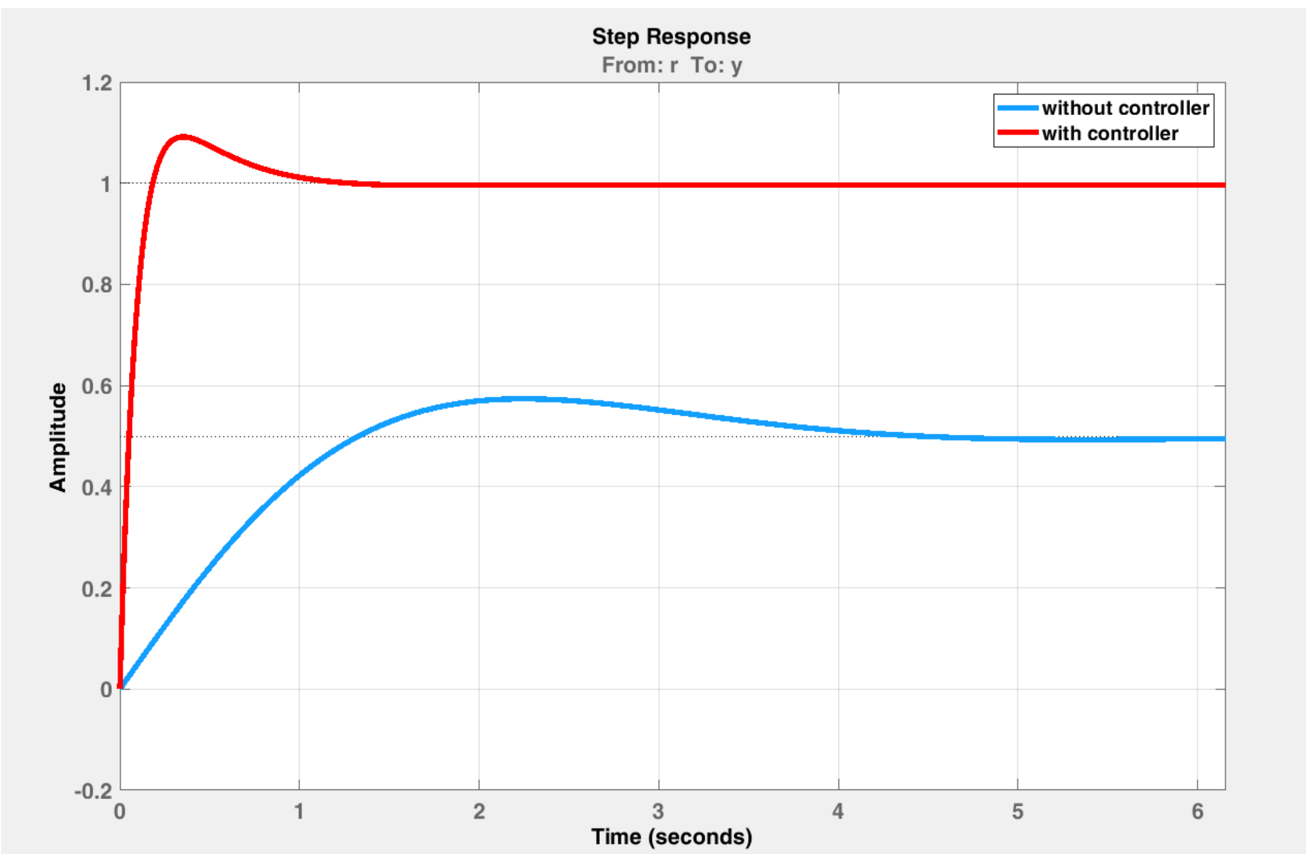


Figure 37: Step response of torque loop with and without controller

Simulation result:

Based on the tuned value of the controllers the torque controller performance has been tested. The corresponding parameter for the simulation has been shown below in Table 6

Table 6: simulation parameter for torque control loop

Parameter name	Parameter value
Wind speed	12 m/s
Proportional gain,Kp_torque	25.21
Integral gain,Ki_torque	37.64
Control mode	Id and iq control
Operating mode	MPPT mode

It is seen that in the beginning the torque shows an abnormal behavior because it goes under a transition period. In the beginning, the required torque for the generator is higher than the steady state condition since in the starting period the angular acceleration is nearly zero. When the generator reaches the rated speed then the torque becomes stable and stationary. Putting these values in the controller the output has been shown below in Figure 38 below.

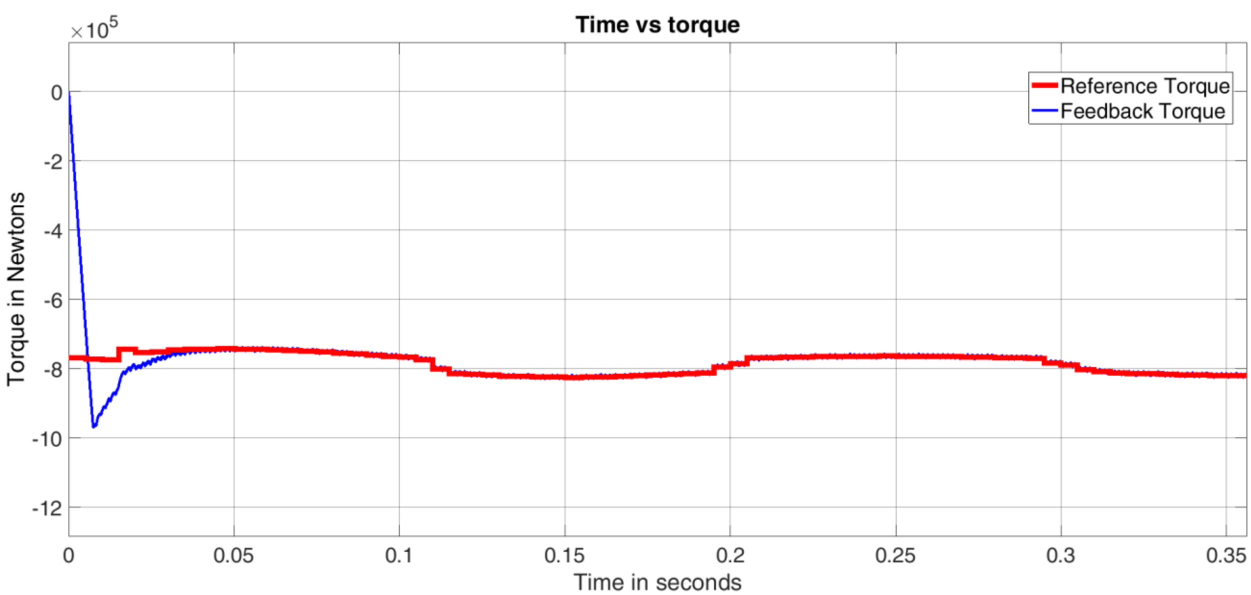


Figure 38: Time vs torque curve

1.2.3 Machine side converter

The design procedure and calculation of the Machine side converter (MSC) parameters are out of scope of this master thesis. However, in order to connect the wind turbine to provide power to the dc link capacitor the design procedure and calculated value of the converter for this PMSG has been taken from [3] The parameter for the MSC has been summarized in the table below:

Table 7: Machine side converter parameter list [3]

Parameter name	Parameter value
DC link capacitor	0.5F
Flying capacitor	0.02F
Converter type	3 Level flying capacitor
Switching frequency	2500Hz
Modulation index	0.83

Output of the MSC:

The output current, voltage of the MSC of phase A is shown in Figure 39 below.

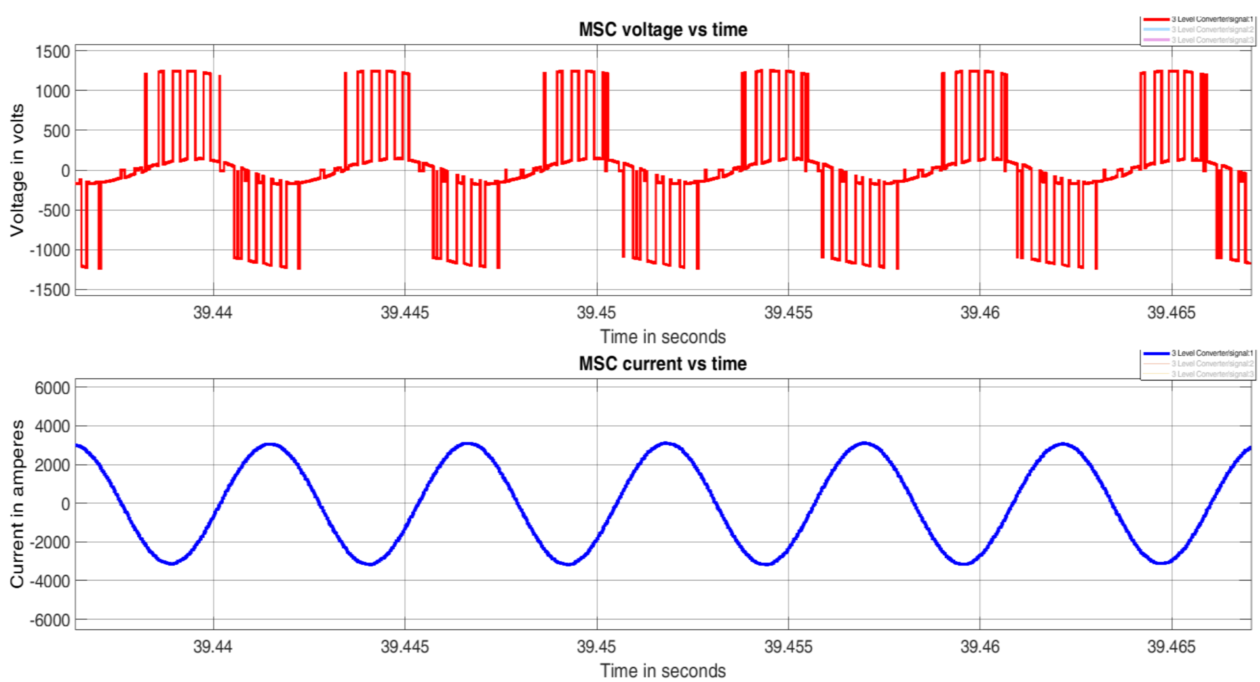


Figure 39: MSC phase A voltage and current

2.1 LCL filter design

Filter: Electrical filters are circuits those can pass certain band of frequencies and block a certain range. [11]

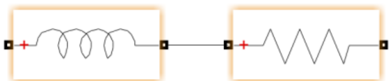


Figure 40: RL Filter

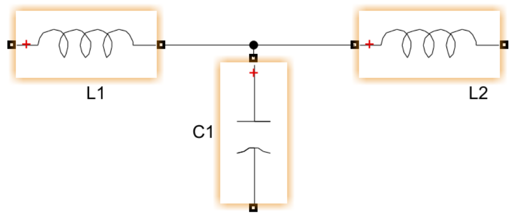


Figure 41: LCL filter

Importance of filter:

The filters are needed to produce a high quality ac power from the existing dc power available in the dc link capacitor or in a dc source. This acts as an interface between the renewable energy source and the power grid. [14]

In electrical engineering, IGBT/MOSFET power switches which are used in commercial grid-connected inverter can be classified as voltage source/sinks so as the ac sources are also voltage sink. From the basics of two port network, if the input is the voltage, the output must be the current, and vice-versa. It means that a voltage source cannot be connected at a voltage sink. In this case that means a direct connection between IGBT switches and grid confronts basic physical law.

Logically, it can be realized the role of filters in grid side converters.

In a RL filter the MOSFET/IGBT switches generate voltage (input) and the output of the inductor is the current which fits the previously described logic of two port network and it can deliver power to the grid.

In case of LCL filter, these switches generates in input voltage for the inductor L1 and the output of this inductor is current. The output of inductor L1 produces current to the capacitor C1.The input of C1 is current and output is voltage. In next phase, the input of inductor L2 is voltage and the output of this inductor is current which supports the rules of two port network.

By applying the same explanation, it can be said that it cannot be put an LC or RLC (low-pass filter) between power switches of converters and grid. [15]

Advantages and disadvantages of RLC and RL filters:

The LCL filter type is recommended in particular for grid tied applications, because the second inductor performs the task to make the system stable in case of any grid parameters fluctuation. This type of filters have the ability to extremely abate the current ripple in spite of having a lower value of inductance. Where as in case of LC configuration it takes a higher size of inductance. [16]

In case of RL filters they drop the output voltage in comparison with the LCL filters. The voltage regulation is also poor, ripple factor is high for light loads. It is not suitable for light loads as ripple factor is directly proportional to the load resistance RL. It also produces some kind of audible noise and it is more bulky and costly. [17]

Why LCL filter is chosen:

For this thesis work on grid side application the LCL filter has been preferred because of cost effective attenuation in comparison to the L filters and LC filters of the switching frequencies. Additionally, it reduces the harmonics of the switching frequencies of the grid currents.

In the next section, the complete procedure of LCL filter design is explained in details.

2.1.1 LCL filter design

The phase voltage spectrum consists of several frequencies as shown in Figure 42. Among them the frequencies those are very much near to the switching frequency fpwm are very much important to filter out. ,,Due to the low pass nature of the filter, the voltage component at fpwm causes the output current response which is two times larger than the same voltage at 2.fpwm.'' [1]As a result the frequency components nearby to the fpwm has a prevailing effect on the rms value of the current ripple. The LCL filter performs to attenuate the frequencies 2*fpwm,3*fpwm and the integer multiples of fpwm.

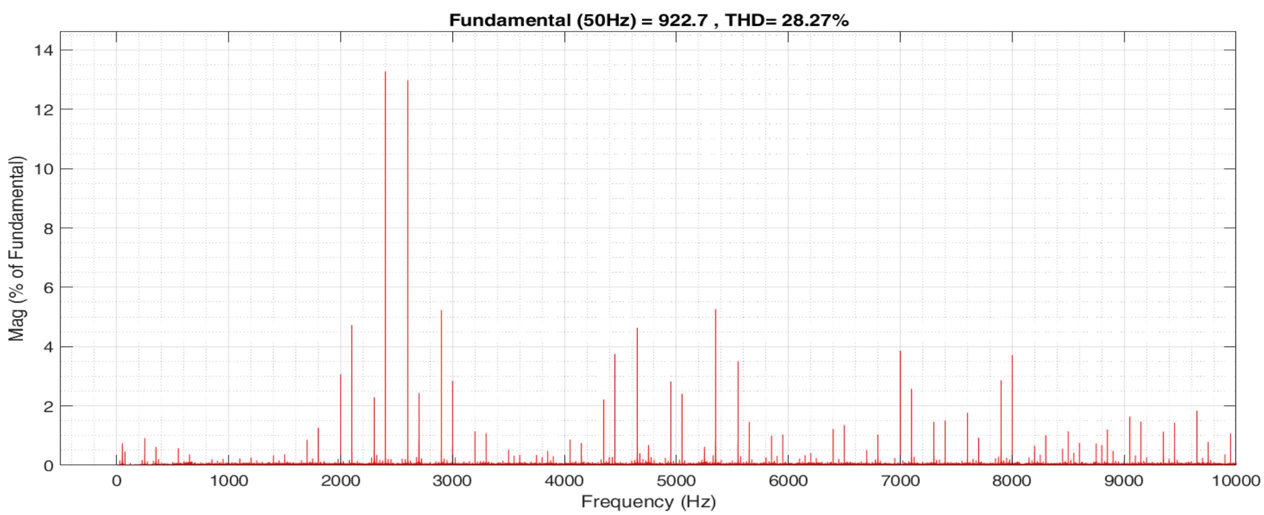


Figure 42: Frequency spectrum of phase A without filter

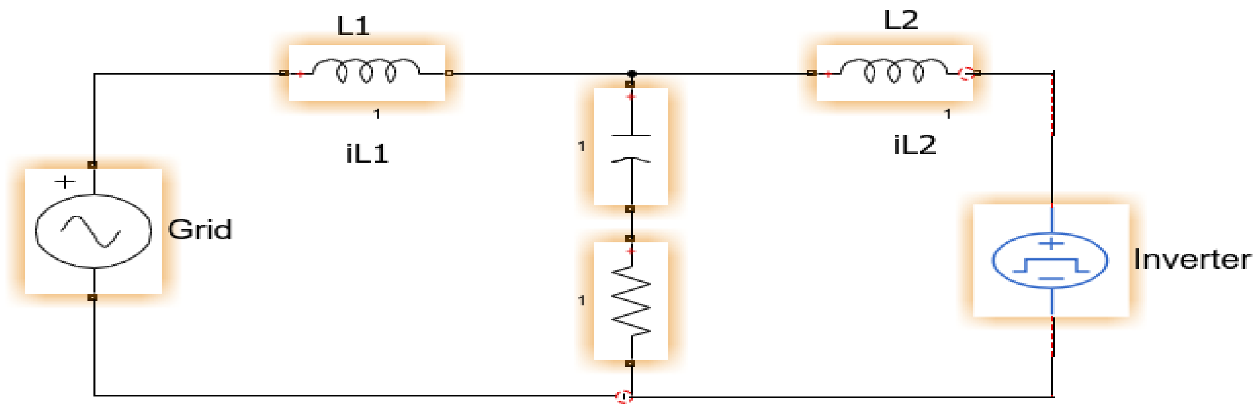


Figure 43: LCL filter suppresses the pwm injection related ripple current from the grid side inverter [1]

The inverter generates power and through the LCL filter this power is fed into the grid. The complete equivalent circuit diagram is shown in the Figure 43 above. The inverter produces pulsed voltages which consists component at the switching frequency. It is worth mentioning here that the grid has no voltage at that particular switching frequency since the grid frequency is 50Hz but the carrier frequency is 2500 Hz. So, it can be assumed that at that particular switching frequency the grid has no voltage [1]. Let us assume that the inverter voltage is U_{inv} and the grid voltage is U_{grid}.

From the above discussion this can be summarized that,

At the switching frequency-

U_{inv}=U and U_{grid}=0.

Uc,iL1,iL2 are the capacitor voltage, inductor current through L1,inductor current through L2 respectively at that switching frequency.

The impedance across the capacitor is [1],

$$z_c = \frac{1}{2 * pi * f_{pwm} * C_1} \qquad (4)$$

(Where,Zc=impedance of capacitor,fpwm=pwm switching frequency,C1=filter capacitance)

is very low, as well as the voltage Vc. Thus the ripple current can be calculated assuming that Vc=0.The rms value of the inductor current can be can be calculated by using this equation [1]:

$$iL1_{rms} = \frac{E * T_{pwm}}{8 * L_1 * \sqrt{3}} \qquad (5)$$

(where,Tpwm=switching time,E=Voltage across the capacitor,L1=inductance of filter)

The inductor current iL_{1rms} performs two tasks. First one is, it charges the capacitor and the second one is it injects the current to the grid. The main goal to use a LCL filter is to reduce the ripple current, iL_{2rms}.Considering the pwm frequency analysis the rms value of the current iL2 is [1]-

$$iL2_{rms} = \frac{iL1_{rms}}{1 - L_2 * C_1 * w_{pwm}^2} = \frac{pi * E}{4 * \sqrt{3} * L_1 * w_{pwm} * (1 - L_2 * C_1 * w_{pwm}^2)} \qquad (6)$$

Where,

$w=2*pi*f_{pwm}$

Design of the LCL filter consists of the selection of the suitable values of the L1,L2 and C1 components. The goal is to reduce the ripple current on the inverter side and the ripple current in the grid side [1].

The ripple current i_{L1} has only a small effect on the rms value of the inverter current but when it passes through the semiconductor switches then it increases the peak value of the current. Hence, while designing the system it is to be considered that the peak value of the ripple current is .3*In (In=rated current).This makes the rms value of the ripple current i_{L1} of In*sqrt(3)/10(roughly 17%).Additionally, the maximum limit of the harmonics of the current should not be above a certain value. According to IEEE-519 standard this value in the range of several kHz should not be above .3% of the rated current. So, the rms value of the ripple current i_{L2} must be below .003*In [1].

Apart from the two factors mentioned above, some other factors should be kept in mind such as the size of the LCL components and the undesirable resonance. When a capacitor is connected in parallel with the system, it increases the reactive power. Generally, it is found that this reactive power is around 5-10% of the rated power. The inductors causes a voltage drop in the input voltage at the rated line frequency. The voltage drop across each inductor should not cross the limit 5% and in total remain below 10%.In addition to these factors another important aspect should be remembered that the LCL filter should not form resonance [1].

The factors those should be considered while designing a LCL filter can be summarized as [1]:

Reactive power of the capacitor,

$$Q_C = C_1 * w_F * U_n^2 < \frac{U_n * I_n}{20} \tag{7}$$

$$=> C_1 < \frac{I_n}{20 * w_F * U_n} \tag{8}$$

Where,

U_n =rated voltage,

W_F =line frequency (grid frequency),

I_N =rated line current,

C1=Capacitance of the capacitor connected in parallel.

The total voltage drop across the inductors at line frequency [1],

$$(L_1 + L_2) * W_F * I_n < \frac{U_n}{10} \tag{9}$$

$$=> L_1 + L_2 < \frac{U_n}{10 * w_F * I_n} \tag{10}$$

Where, L_1, L_2 are the line inductances.

U_n = rated voltage,

W_F =grid frequency,

I_N =rated line current,

The resonance frequency of the LCL filter is,

$$W_{LCL} = \sqrt{\frac{L_1 + L_2}{L_1 * L_2 * C_1}} \tag{11}$$

$$w_F \ll w_{LCL} \ll 2 * pi * f_{PWM} = w_{PWM} \tag{12}$$

2.1.2 Calculation of the LCL parameters

For this grid connected inverters the rated values mentioned below:

Line curren, In calculation:

Total power, S=1.5MVA.The power factor is considered to be 0.6.Hence, the real power is P=1.5*10^6*.6=0.9MW.

The relation between three phase power, voltage, and current is-

$$P = \sqrt{3} * V_L * I_n * COS\theta$$

Here,

P=0.9MW, Line to line voltage,V_L=690V and COSθ=0.60(power factor at worst case) .Putting all these values in the above equation:

In=1255A.

The parameters to calculate the filter components has been mentioned below:

Parameter name	Parameter value	Parameter name	Parameter value
In,the line current	1255A	Switching frequency, Wpwm	2500Hz
E,dc bus voltage	1217V	Un, line to line voltage	690V
Tpwm, switching time	1/2500 Hz	$W_{F,}$ grid frequency	50Hz

Here,

$$iL_{1rms} = \frac{In * \sqrt{3}}{10}$$

Putting the values from the above table, iL1rms =1255A.

From equation 7-

$$iL1_{rms} = \frac{E * T_{pwm}}{8 * L_1 * \sqrt{3}}$$

E=1217V; $T_{PWM} = \frac{1}{2500Hz}$;

Putting all the values in equation 7 the calculated values of inductor

L_1= 1.6162e-04 H

From equation 10-

$$=> C_1 < \frac{I_n}{20 * w_F * U_n}$$

Putting the values in this equation the upper value of the capacitor is,

C_1<2.8948e-04 F

Hence, C1 must be chosen in such a way that it is below 8.69*10^-3   F

From equation 12-

$$=> L_1 + L_2 < \frac{U_n}{10 * w_F * I_n}$$

If all the values calculated above are put in this equation then the value of L2 can be estimated. By putting all the values,

$$L_1+L_2< 3.1831e\text{-}04\ H$$

The value of L1 is taken as **L1=1.6162e-04H**. Hence, the value of

$$\mathbf{L_2 = 1.5669e\text{-}04H}$$

The filter parameter value can be summarized as:

L1	**1.6162e-04H**
L2	**1.56e-04H**
C1	**2.89e-04 F**

Sample Matlab code:

The sample matlab code to determine the LCL filter parameters has been shown below

```
%% filter parameter calculation

ln=1255;

Un=690;

wf=2*pi*50;

il1_rms=ln*sqrt(3)/10;

E=1217;

t_final=.0004;

t_initial=0;

fc=1/(t_final-t_initial)

T_pwm=1/fc;
```

```
%first inductor calculation

L_1=(E*T_pwm)/(8*il1_rms*sqrt(3));%the inductor value must be less than this

%capacitance calculation

C_1=ln/(20*wf*Un); %the capacitor value must be less than this

%second inductor calculation

L_2=Un/(10*wf*Un)-L_1; %the inductor value must be less than this
```

Output:

L_1 = 1.6162e-04

C_1 =2.8948e-04

L_2 =1.5669e-04

2.1.3 Transfer function calculation of LCL filter

In order to find the transfer function of this filter it is considered as a two port network. In this section firstly, a brief introduction of a two port network will be presented then the corresponding Z parameters calculation process will be discussed. After that the transfer function calculation is shown in details.

2.1.4 Two port network

A two port network is a network in which current enters through one port and leaves through another port. [2]The typical block diagram of a two port network is shown in Figure 44.

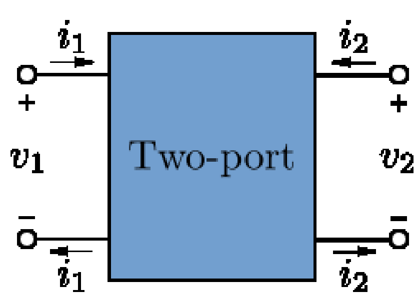


Figure 44: Two port network [2]

The generalized equation of a two port network-

$$V_1 = I_1 * Z_{11} + Z_{12} * I_2 \qquad (13)$$
$$V_2 = I_1 * Z_{21} + I_2 * Z_{22} \qquad (14)$$

Where,

V_1=Input port voltage level.

I_1 =Input port current.

V_2=Output port voltage level

I_2=Output port current level.

Z_{11}=Impedance between input voltage and current when output port is open circuited.

Z_{12}=Impedance between input voltage and output current when input port is open circuited.

Z_{21}=Impedance between output voltage and input current when output is open circuited.

Z_{22}=Impedance between output voltage and output current when input is open circuited

2.1.5 Z parameters calculation of LCL filter

The simplified model of the LCL filter has been shown in Figure 45 below. First of all the Laplace transform of the inductors, capacitors has been taken then the corresponding z parameters has been calculated.

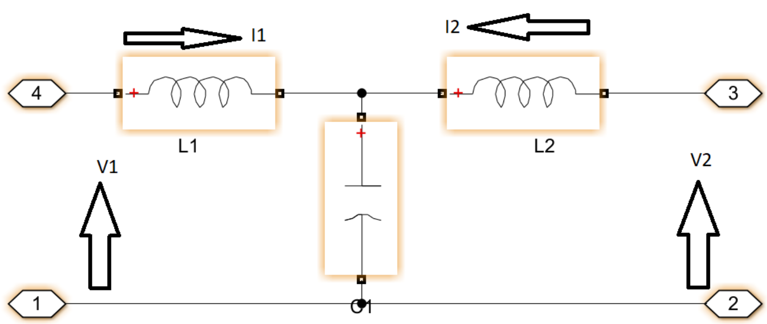


Figure 45: Two port network of LCL filter

From equation 15,

$$V_1 = I_1 * Z_{11} + Z_{12} * I_2$$

Let us assume that the current in the output side I2=0(open circuited) then the two port network becomes as shown in Figure 46.The ratio between the input side voltage and current is Z11.

Hence,

$$Z11 = s * L_1 + \frac{1}{s * C_1}$$

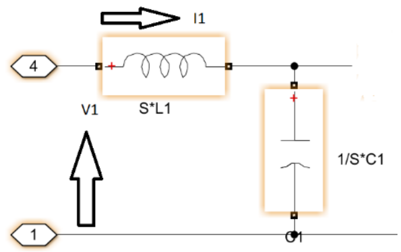


Figure 46:Z11 parameter circuit diagram

Similarly, in order to calculate the impedance value of Z12, let us assume that the input side is open circuited and the input current I1=0.The two port network takes the shape of the circuit shown in Figure 47.

Hence,

$$Z12 = \frac{1}{S * C1}$$

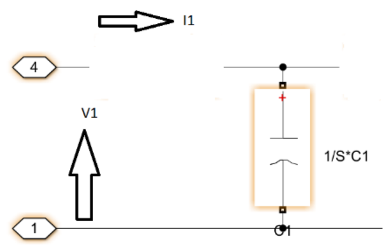


Figure 47:Z12 parameter calculation

The parameters Z21 and Z22 are calculated in the same way. The corresponding values calculated are mentioned below (for Z21,the value I2 is taken as zero. For Z22,the value I1 is taken as zero):

$$Z21 = \frac{1}{S * C1}$$

$$Z22 = s * L_2 + \frac{1}{s * C_1}$$

2.1.6 Transfer function calculation:

From equation 15 & 16 we get-

$$V_1 = I_1 * Z_{11} + Z_{12} * I_2$$
$$V_2 = I_1 * Z_{21} + I_2 * Z_{22}$$

By using the values of I1 from equation 16-

$$I_1 = \frac{V_2 - I_2 * Z_{22}}{Z_{21}}$$

Putting the values of I1 in equation 15-

$$V_1 = \frac{V_2 - I_2 * Z_{22}}{Z_{21}} * Z_{11} + Z_{12} * I_2$$

$$=> V_1 = \frac{V_2 * Z_{11} - I_2 * Z_{22} * Z_{11} + Z_{12} * Z_{21} * I_2}{Z_{21}}$$

$$=> V_1 * Z_{21} = V_2 * Z_{11} - I_2 * Z_{22} * Z_{11} + Z_{12} * Z_{21} * I_2$$

The value of V_2 has been taken as 0 since the inverter V_1 is only supplying power to the system and there is no power coming from grid to the system. In the two port network the resulting current entering to the system and coming out of the system is I_1.

Hence the equation above becomes-

$$=> V_1 * Z_{21} = -I_2 * Z_{22} * Z_{11} + Z_{12} * Z_{21} * I_2$$

$$=> \frac{I_2}{V_1} = \frac{Z_{21}}{- Z_{22} * Z_{11} + Z_{12} * Z_{21}}$$

Since the current direction in the LCL filter of I_2 is opposite of the two port network the above equation of the transfer function becomes-

$$=> \frac{-I_2}{V_1} = \frac{Z_{21}}{Z_{22} * Z_{11} - Z_{12} * Z_{21}}$$

Putting all the values of the Z parameters, the above equation it takes the form-

$$TF_{LCL} = \frac{1}{L_1 * L_2 * C_1 * s^3 + (L_1 + L_2) * s} \qquad (17)$$

This is the standard transfer function of the LCL filter.

2.1.7 Bode plot of LCL filter

The bode plot is a control system analyzer tool through which a system can be analyzed whether it is stable or unstable. In equation 17 the values of the inductors, capacitors are put and then the bode plot has been drawn by using the matlab control system analyzer tool.

The open loop transfer function-

$$TF_{LCL} = \frac{1}{L_1 * L_2 * C_1 * s^3 + (L_1 + L_2) * s}$$

Then, the open loop transfer function-

$$\mathrm{TF}_{\mathrm{LCL(open\ loop)}} = \frac{1}{4.945e - 11\ s\text{^}3\ +\ 0.0001323\ s}$$

Sample code for determining the open loop transfer function calculation:

```
% %% transfer function of LCL filter
L1 = 1.6162e-04
C1 =2.8948e-04
L2 =1.5669e-04
lcl_num=[1]
lcl_den=[L1*L2*C1 0 L1+L2 0]
tf_lcl=tf(lcl_num,lcl_den)
```

Output:

tf_lcl =

1

4.945e-11 s^3 + 0.0001323 s

After determining the open loop transfer function the bode plot is drawn in Figure 49 below. In the bode plot there is a spike at the resonance frequency. At this frequency the gain margin and phase margin becomes positive. Hence, the system turns out to be an unstable system. In order to overcome this situation there must be some kind of mechanism so that the spike goes away and the system recovers itself from instability.

In the next section the detail process to make the system stable has been discussed.

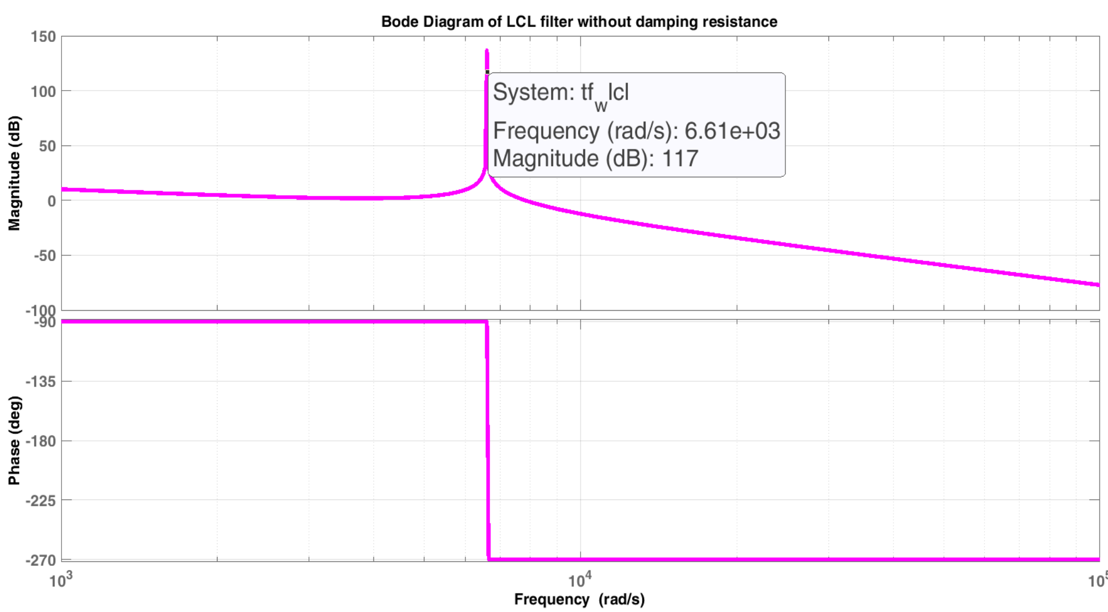


Figure 48: Bode plot of LCL filter without damping resistance

2.1.8 Resonance damping methods

The denominator of the closed loop transfer function is a third order system. If the denominator is closely analyzed then it is seen that the second order term is absent. For this reason the system is becoming unstable. There may be some values resistance can be added with the system so that the second order term comes to the denominator of the transfer function and the system becomes stable.

In this section the damping method of the resonance frequency has been discussed. There are different ways to connect a damping resistance with the LCL filter shown in Figure 50.

In combination 1 a resistor has been connected in series with the inductor in series. There is a problem with this method that the low frequency gain will be reduced since the inductors will show low impedance but the resistors will introduce a significant amount of high impedance. On the other hand at high frequencies it will not affect the performance of the LCL filter since the inductor will show a high value of impedance in comparison to the resistor in high frequencies so there is no effect of the series resistor and it can be ignored. Hence, this combination has not been taken for damping methods.

The combination 2 is not suitable for high frequency range because at high frequencies the series inductor will show a high impedance but the parallel connected resistor will show a low impedance and the power will not be filtered out at high frequencies. As a result, this combination is also avoided.

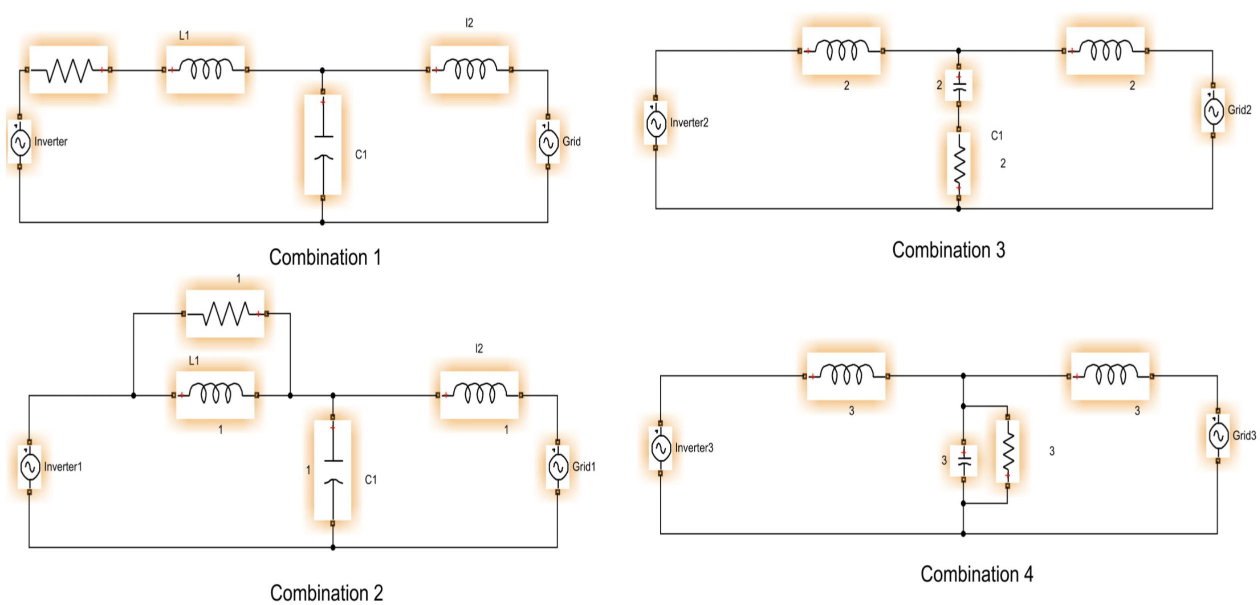


Figure 50: Damping methods of LCL filters

The combination 3 where a series resistor is connected with the capacitor will reduce the ability of the filter to filter out the high frequency harmonics. On the other hand at low frequencies, the capacitor shows a high impedance so the effect of resistor can be ignored.

The combination 4, here the resistor is connected in parallel with the capacitor. This combination has no effect on the low and high frequency range. At low frequencies, the inductor impedance of L_2 is much smaller than the parallel connected resistor. So, no current will flow through the resistor. At high frequencies, the capacitor acts as a short circuit so the resistor will do nothing.

From the above combination it can be seen that the combination 4 shows the best performance as a damping solution. However, there is a problem with this solution. Since the voltage drop through the inductor L_2 is relatively small, the capacitor voltage is approximately equal to the grid voltage which is applied directly parallel to the resistor turning to a higher power loss.

Thus, this solution is avoided because of this reason. Comparatively, the combination 3, the resistor in series with the capacitor is widely used for the damping solution and in this thesis this has been taken as a damping solution. [14]

2.1.9 Determination of damping resistance

In this section, first of all the transfer function of the combination 3 shown in Figure 1 has been calculated. Then, the approximate damping values has been assumed. After that the damping resistance is calculated. Finally, the bode plot of the closed loop transfer function has been pointed out to show that the resonance spike has been removed from the bode plot.

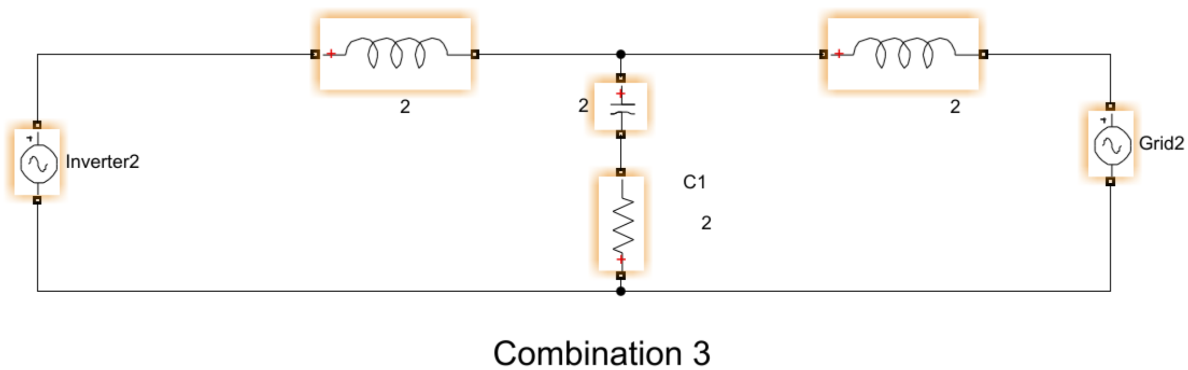


Figure 51: Damping of LCL filter

The open transfer function of the combination 3 is (X. Ruan et al., Springer Nature Singapore Pte Ltd. and Science Press 2018)-

$$TF_{LCL(open\ loop)} = \frac{R_1 * C_1 * s + 1}{L_1 * L_2 * C_1 * s^3 + (L_1 + L_2) * C_1 * R_1 * s^2 + (L_1 + L_2) * s} \tag{18}$$

In order to calculate the damping resistance the resonance frequency has been calculated first.At that resonance frequency the impedance of the filter capacitance has been calculated. This value of impedance has been taken the equivalent value of the resistance. (Dr. L.Ravi Srinivas1, June 2016)

The LCL filter resonance frequency taken from the bode plot below in Figure 2.It is seen that the value of the resonance frequency is 6.61e3 rad/s.At this frequency the impedance of the capacitance is:

$$Z_c = \frac{-j}{2 * pi * f_R * C1}$$

Where,

Parameter name	Parameter value
f_R =Resonance frequency	6.61e3 rad/s
Filter capacitor,C1	1.4e-4F

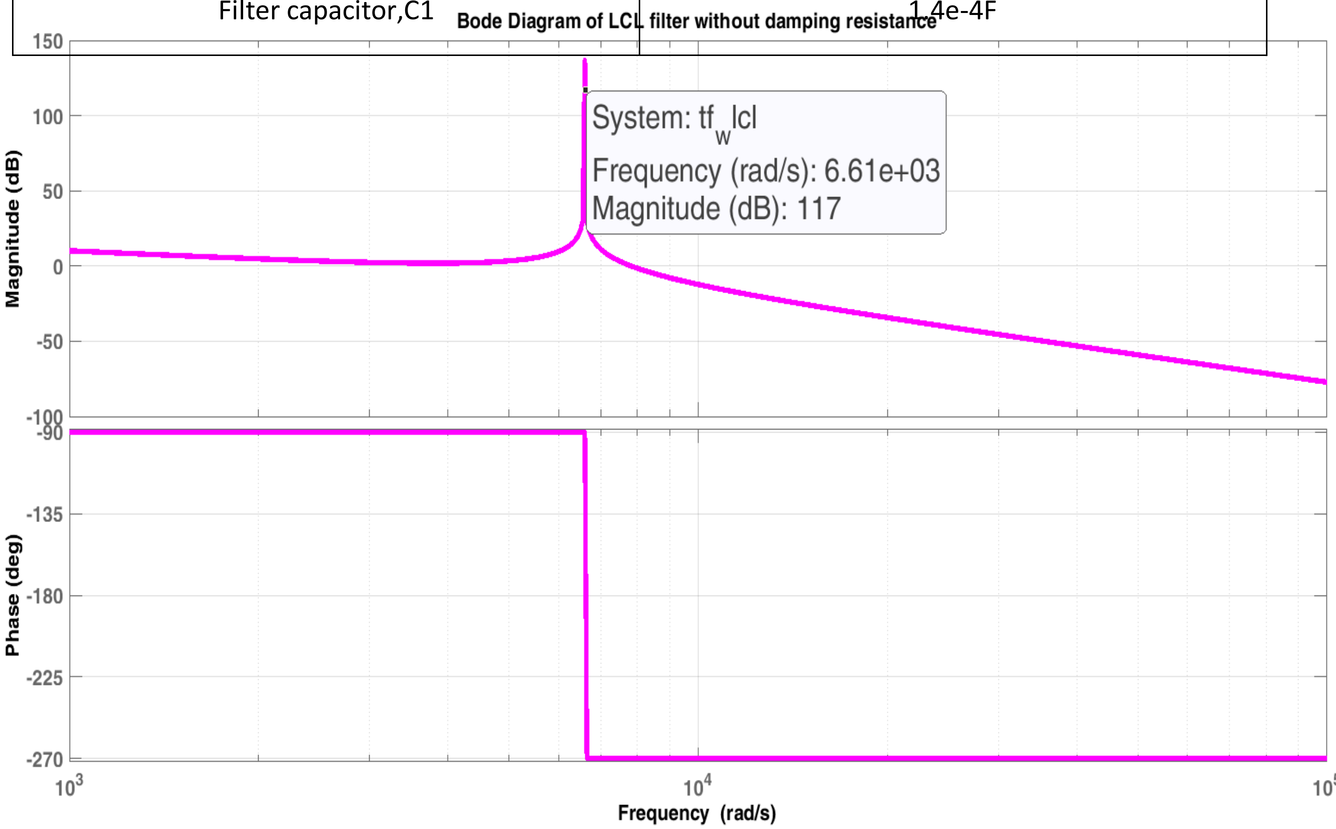


Figure 52: Bode plot of lcl filter with damping

Putting all the values in the above equation the impedance of the capacitor is calculated as-

Zc= - 0.5226 j Ω

So, the numerical value of the filter resistor should be **0.5226 Ω**

Putting this value as the damping resistance the corresponding bode plot has been shown in (Dr. L.Ravi Srinivas1, June 2016)below. However, this damping resistance is not fully capable to damp the resonance frequency. So, the value of the resistance has been increase from this value to 5 Ω with a 1Ω interval to see the performances of damping.

Sample matlab code:

The matlab code to see the performance of different damping resistance is mentioned below:

```
for i=1:1:5
L2= 1.56e-04;
L1=1.6162e-04;
C1=2.89e-04;
R1=.5226+i-1
tf_num=[R1.*C1 1];
tf_den=[L1.*L2.*C1 (L1+L2).*C1.*R1 (L1+L2) 0];
tf_lcl=tf(tf_num,tf_den)
bode(tf_lcl)
hold on
grid on
end
```

Simulation result:

The simulation result of the matlab code is shown below. Here, it is seen that only the resistance value .2646 ohm shows a poor performance for damping but the other resistance values show better damping, almost same and can be taken any one of them as a damping resistance. However, the resistance value 1 ohm has been taken as a damping solution.

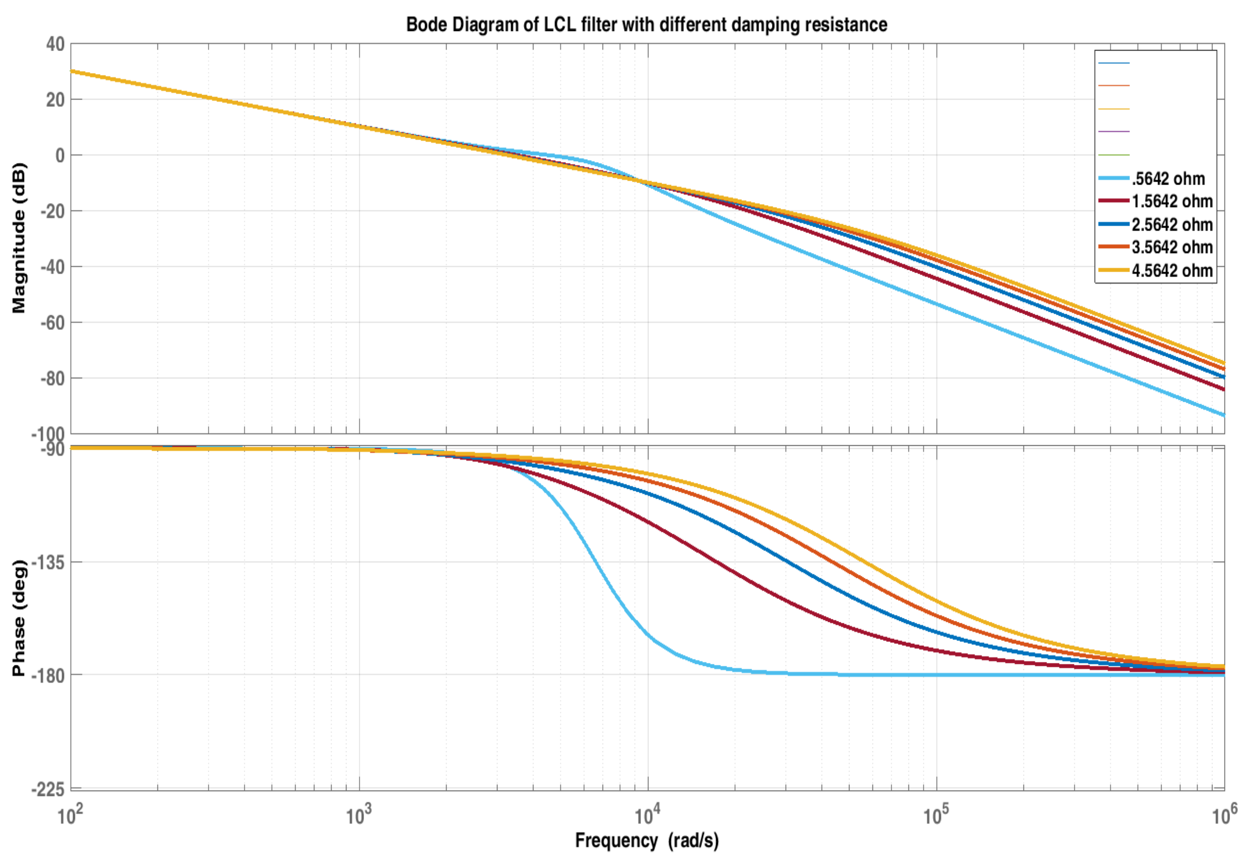


Figure 53: Bode plot of different damping resistances

2.2 Converter design

A power converter is an electrical or electromechanical device which is used to convert the electrical power from ac to dc or dc to ac. [18] In modern power electronics era multi-level converters have created a revolution. [19] Generally, before the introduction of the MMC the voltage level was 2 level but now in modern days the voltage level has been increased by higher levels. Additionally, the back to back connection of this MMC gives dc link 4 quadrant ac-ac conversion. [20] Currently, the usage of power electronic MMC includes HVDC transmission, FACTS, SVC, Photovoltaic and wind generation systems. [21]

In the following sections the popular types of multilevel converters those are being currently used will be discussed first. Next, the flying capacitor topology which has been implemented in this thesis will be explained in details. Then the Simulink model for the converter has been elaborated in details. After that, the simulation result will be shown. Finally, the transfer function calculation of the converter system will be calculated and discussed.

2.2.1 Types of multilevel converters

The multilevel converters can be divided into three types:

- **Flying capacitors multilevel inverter:** ,,The topology is called so because the capacitors float with respect to earth potential'' [22]Capacitor use is the core idea behind this topology. In this system, the capacitors are series connected clamped switching cells. Unlike the diode clamped, there is not needed any kind of clamping diodes. The output voltage is half of the input voltage. [23] A typical circuit diagram for 3 level flying capacitor inverter is shown in Figure 53.

-**Cascaded H- bridge multilevel inverter:** In this topology, less amount of capacitors and switches are required for each level. Power conversion cells are connected in series and for this reason scaling can be done easily. The arrangement of the capacitor and switches pair are like H Bridge and due to their arrangement in such way they can provide different input DC voltage levels. One of the main advantage of this type of converter is that the components required for this converter are less than the other two types of converters. The circuit diagram for a three level H bridge inverter is shown below in Figure 55. [23]

- **Diode clamped multilevel inverter:** The operating principle of this type of inverter is that the diodes provide the higher voltage levels through different phases to the capacitor banks. The voltage transmitting capability of diodes are limited with their characteristics. Because of this property they reduce the stress on the electrical devices. The maximum voltage that can be inverted is half of the input DC voltage. The typical circuit diagram of a diode clamped multilevel inverter has been shown in Figure 54 below. [23]

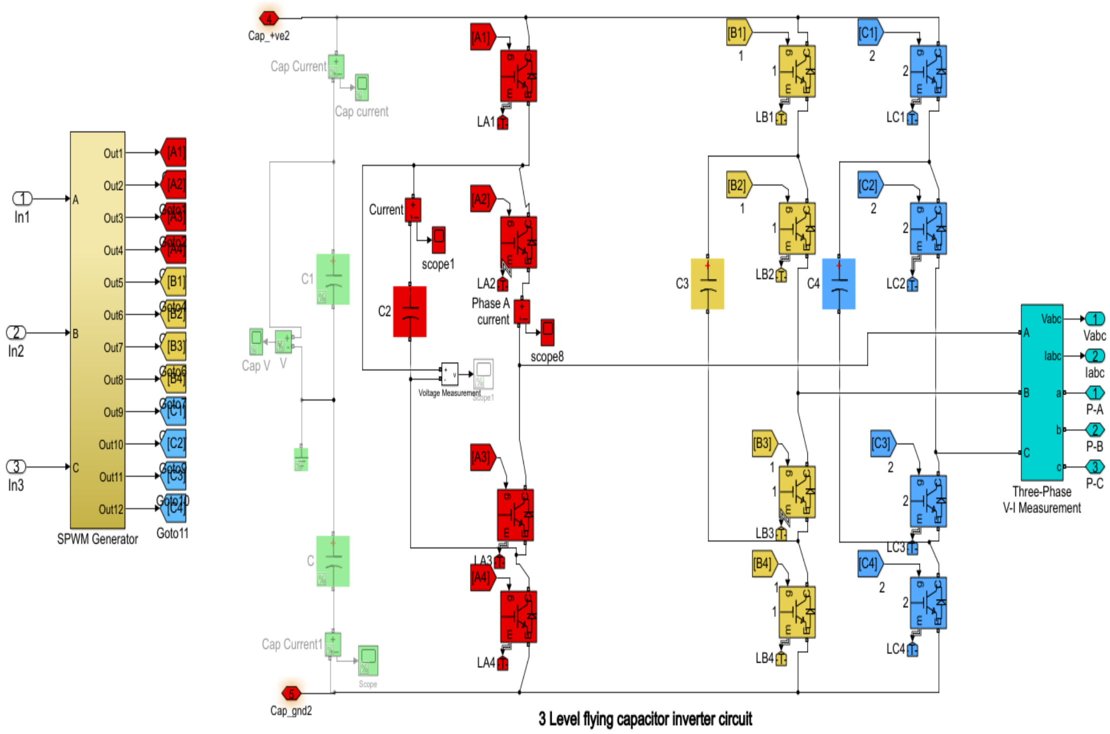


Figure 54: 3 level flying capacitor converter [3]

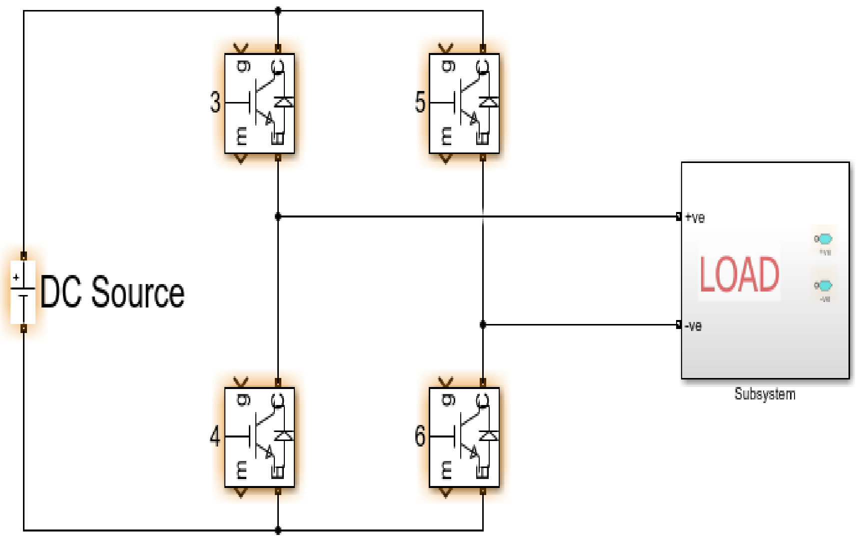


Figure 56: H bridge converter. [5]

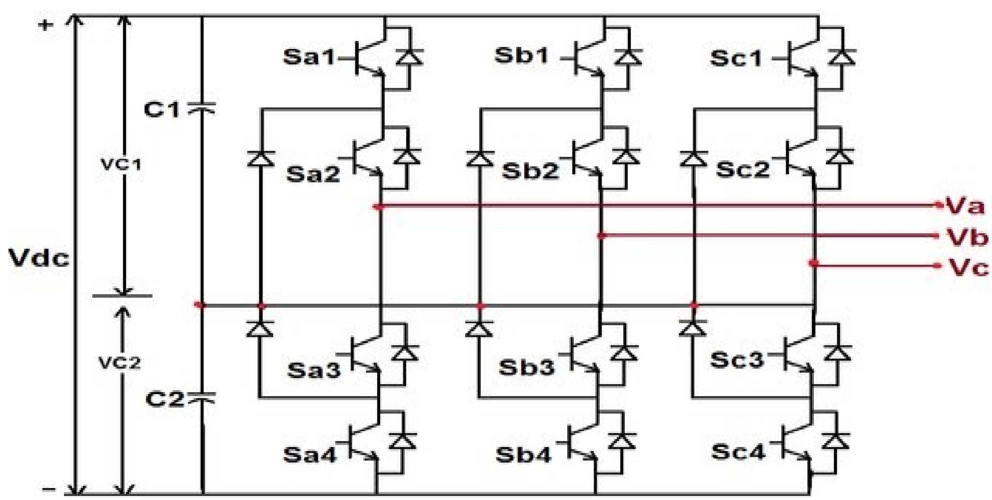


Figure 55:3 level diode clamped inverter. [4]

2.2.2 Flying capacitor topology

For a 3-Level inverter it is needed 2(m-1) main capacitors and (m-1)*(m-2)/2 auxiliary capacitors in each leg in order to construct a m level multilevel inverter. Due to this constructional requirement there are one auxiliary capacitor and two main capacitors needed. [22]

The circuit diagram for a single phase 3 Level inverter is shown in Figure 56 below. In this leg there are 4 IGBT switches, 2 main capacitors and 1 auxiliary capacitor. In order to get the 3 level output voltage, the switching logic has a definite pattern. For example if S1 is on then S21 is turned off and vice versa. This is true for S2 and S11 also.

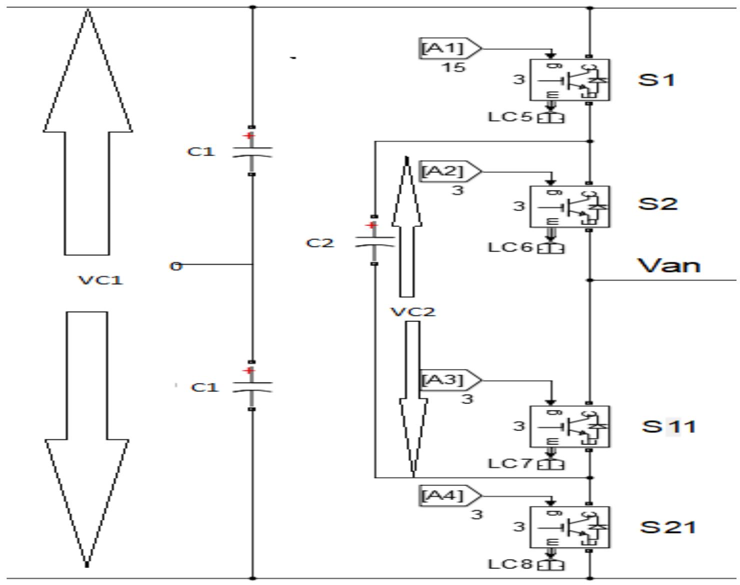


Figure 57: Single leg of a flying capacitor converter [6]

The dc link capacitors marked C1 are charge by means of external resources. Each leg has a mounted capacitor C2.The output voltage is given by [24] [25] [26]-

$$V_{an} = S1 * (V_{C1} - V_{C2}) + S2 * (V_{C2} - V_{C1})/2$$

Where,

S1,S2= 1 when it is conducting,

S1,S2= 0 when it is not conducting,

The switching logic can be summarized in the table below:

Table 8 : Switching state logic of flying capacitor converter [8]

S1	S2	Van	C1
ON	ON	+Vdc/2	NC
ON	OFF	0	+
OFF	ON	0	-
OFF	OFF	-Vdc/2	NC

2.2.3 Modulation Technique

In order to get better output and lower amount of harmonics SPWM method has been used. There is a basic rule for multi-level PWM techniques. To get m level output it is required (m-1) level carrier waves. The frequency and amplitude must be of same value. The basic technique of SPWM method is that the reference wave is compared with the carrier wave. [27] [28]

A typical SPWM technique has been shown in Figure 57 below. In the figure when the sinusoidal signal is higher than the carrier wave then the output is 1 and smaller then the output is 0.

The modulation index is given by-

Ma=Am/2*Ac

Where Am is the amplitude of the modulating signal and Ac is the amplitude of the carrier wave (P-P) [3]

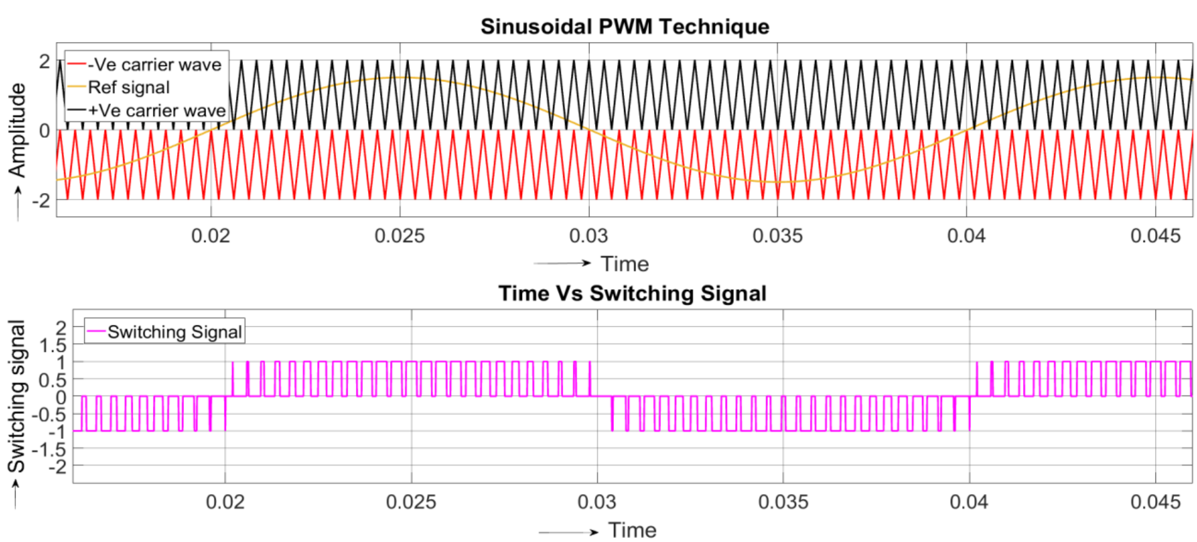


Figure 58: SPWM of 3 level inverter [3]

2.2.4 Simulink model of the converter system

The Simulink model of the converter system receives the controller output from the PI controller of the inner current loop. The three phase output of the controllers' works as three reference phases of the

SPWM generators. The output of the SPWM generators are producing the pulses necessary for the switching of the IGBT switches. The output of the converter system goes to the LCL filter and then to from the filter to the grid. The whole system has been summarized in Figure 58 below.

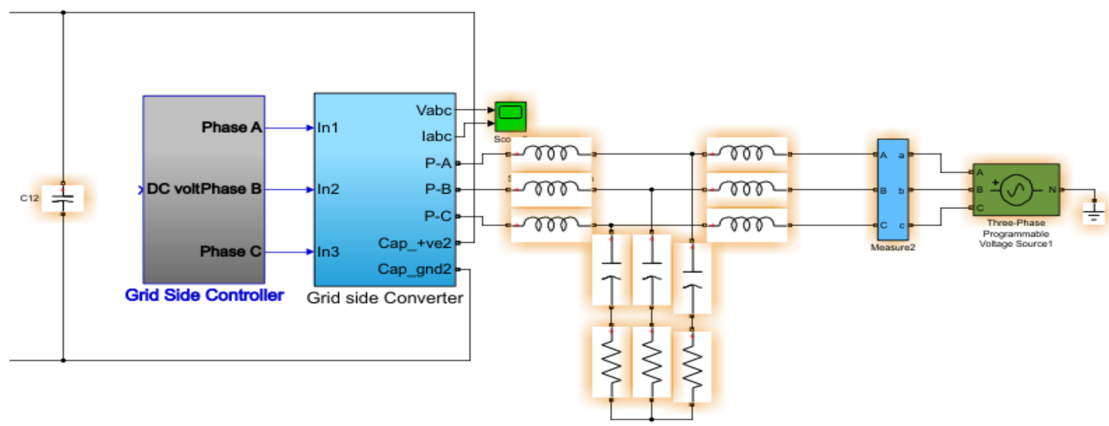


Figure 59: Simulink model of the converter connection

The Grid side converter block consists of a SPWM generator and a 3 level flying capacitor model shown in Figure 59 below. The internal architecture of the SPWM structure has been shown in Figure 60 below. In the SPWM block, it has two parts: Comparator block and switching decision logic block. The purpose of

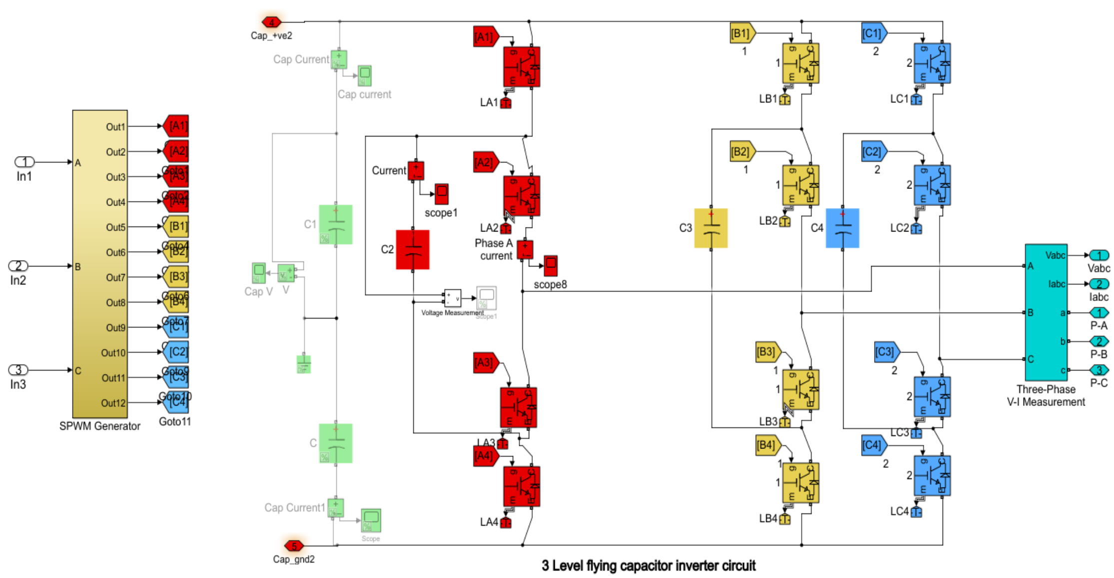


Figure 60: Internal model of converter block

The comparator block compares the reference block with the carrier wave and produces the pulses. The inner model of the comparator block is shown in Figure 61 below. Refer to section 2.3 mentioned above the pulse generation criteria has been described in details.

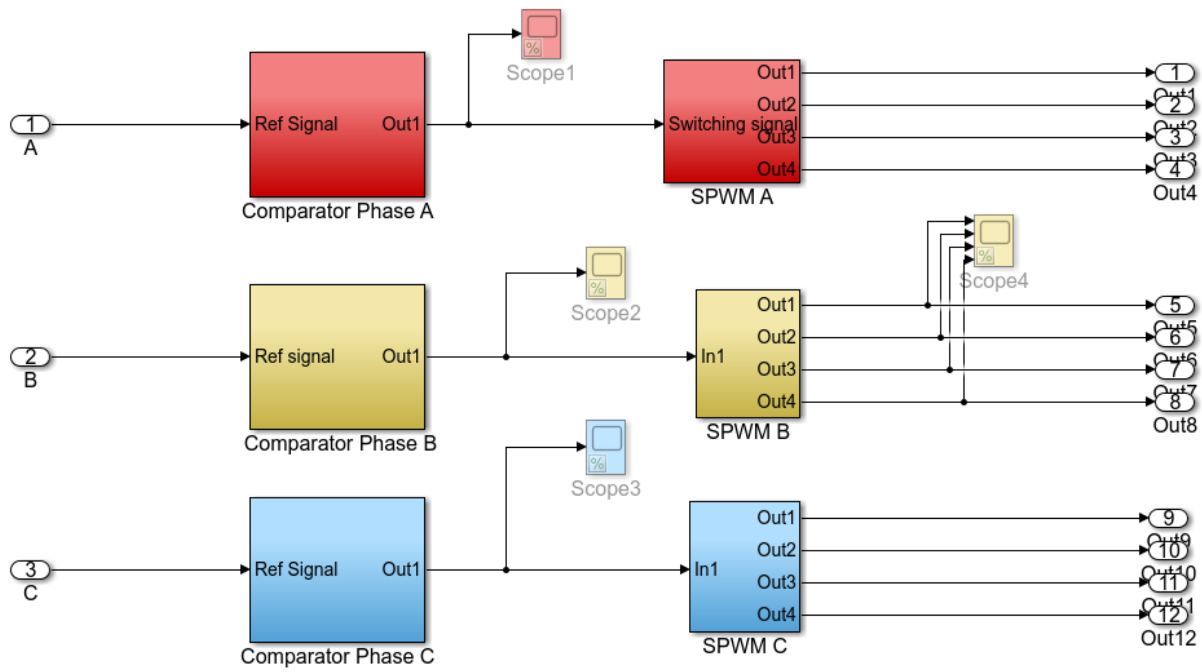
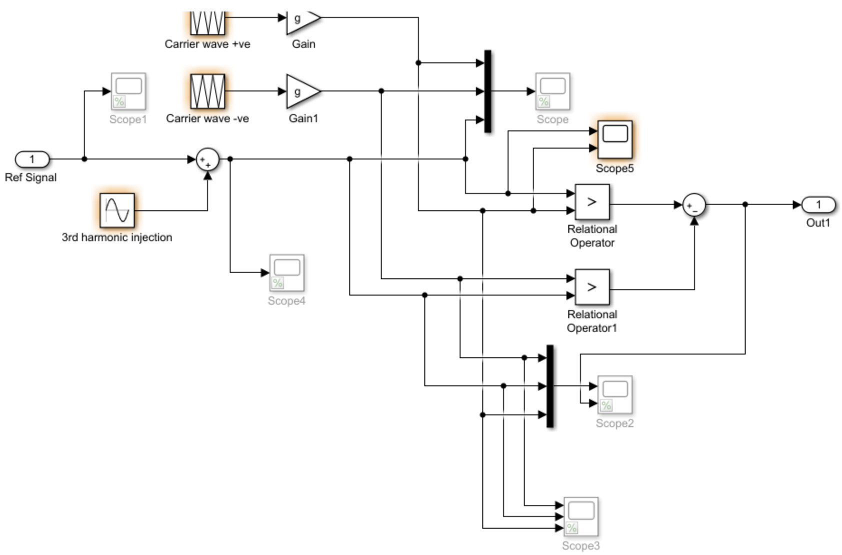


Figure 61: Internal model of SPWM generator



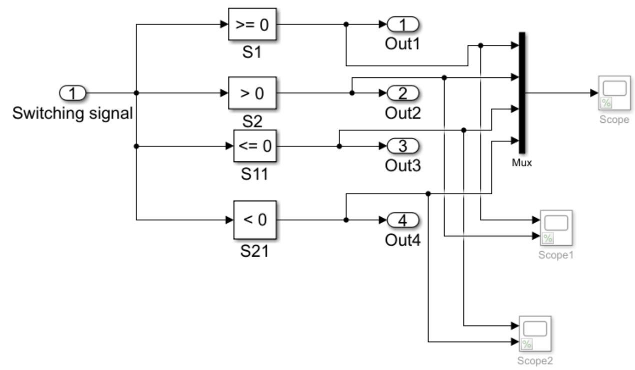


Figure 62: Internal model of PWM block

Figure 63: Internal model of Comparator block

In section 2.2 it has been shown that when the switch S1 has a particular state then what should be the status of the other switches. From that section the idea from there has been implemented here and shown in Figure 62.Each of the logic output is controlling the switches of each leg shown in Figure 59 successively.

2.2.5 Simulation results

In order to simulate the converter system the corresponding standard parameters: carrier frequency, modulation index, flying capacitor capacitance, dc link capacitor has been taken from reference [3]. The standard data has been summarized in Table *9* below.

Table 9: Standard parameter for converter system *[3]*

Parameter name	Parameter value
Carrier frequency	2500 Hz
Flying capacitor capacitance	0.02F
DC link capacitance	0.5F
Modulation index	0.83

The SPWM generator output for the converter system has been shown in Figure 63 below. According to these switching pulses the corresponding switches of the converter will generate the output.

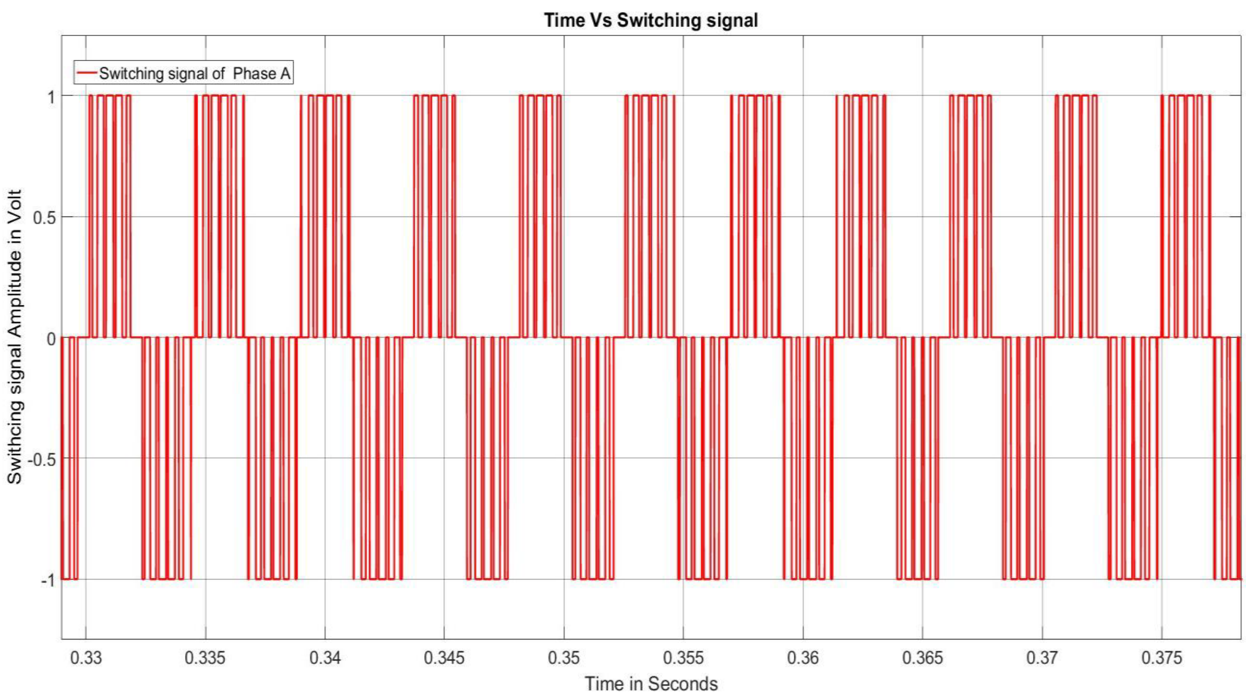


Figure 64: Switching pulses for converter

The output of the converter system passes through the LCL filter. The main task of the LCL filter is to filter out the harmonics of the fundamental frequency. The filtration should be so rigid that the THD value of the current output must remain below 5% [29], according to the standard of converter topology. In order to check whether the simulation results work properly the following parameters has been taken into consideration shown in Table 10 below:

Table 10: Simulation parameter for LCL filter output test

Parameter name	Parameter value
Wind speed	12 m/s
Operation mode	Id and iq control
D axis current on grid,Id_ref	2000A
Q axis current on grid,Iq_ref	0A
Running time	100 Seconds

The output current and voltage to the grid has been shown in Figure 64, Figure 66 respectively below. The corresponding THD value has also been shown in Figure 65 and Figure 67 below respectively. The THD value has been kept below 5%.

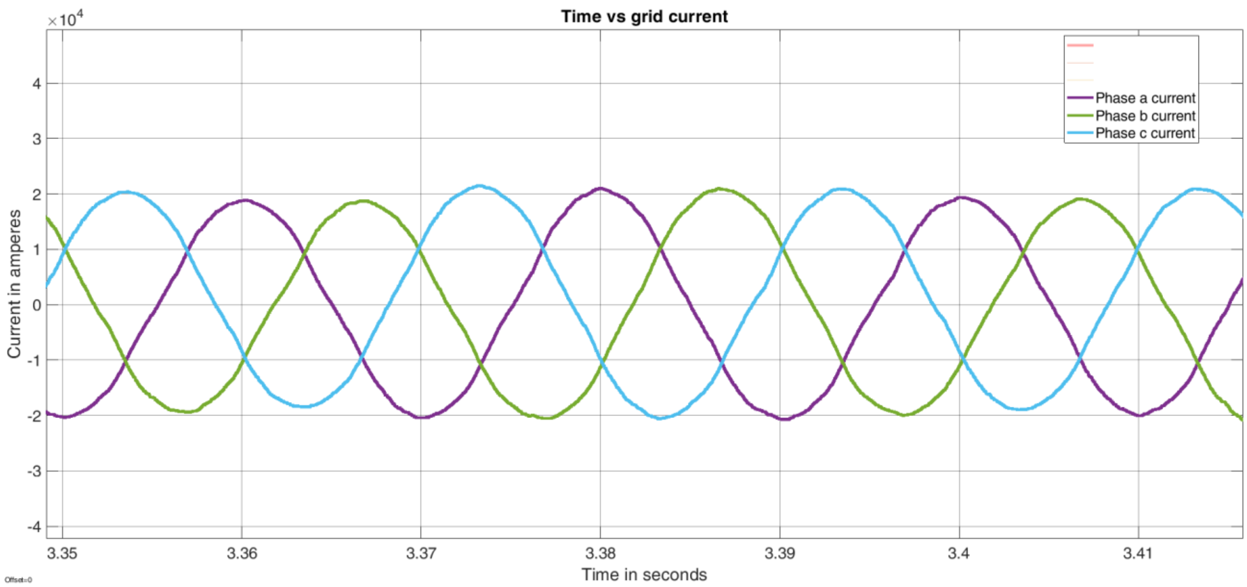


Figure 65: Time vs grid current

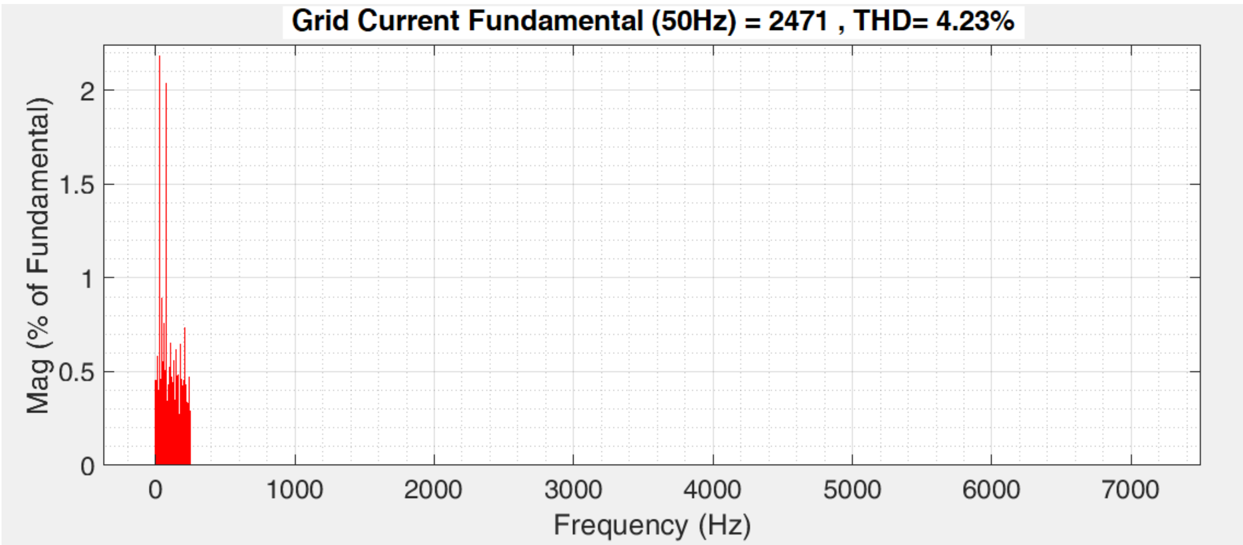


Figure 66: Frequency spectrum of grid current

Figure 67: Grid voltage vs time

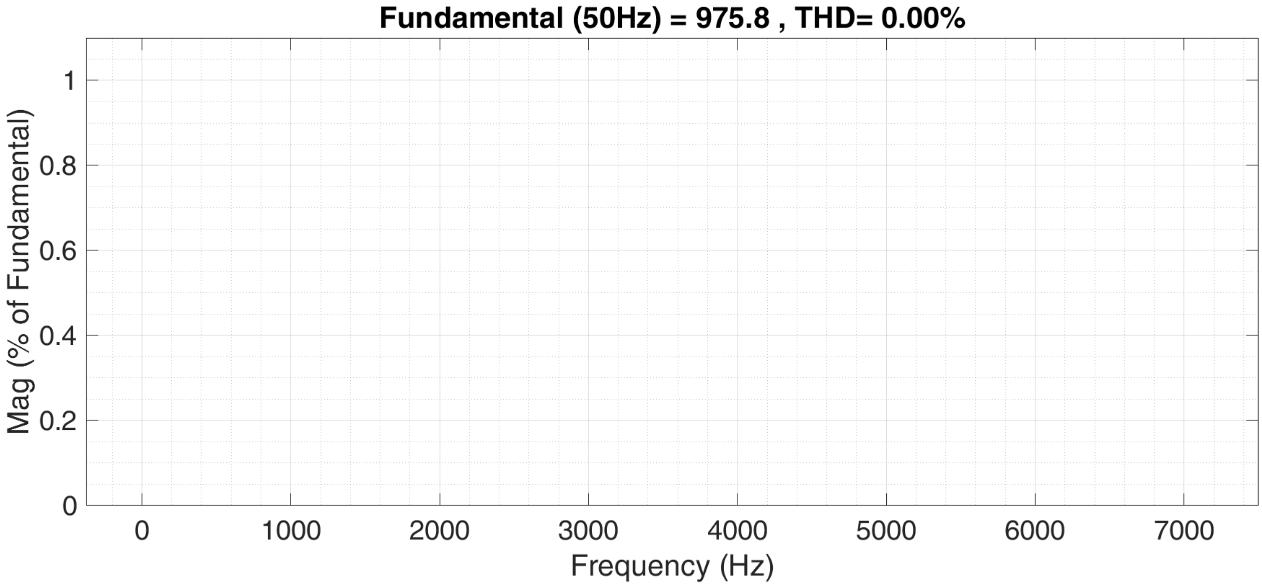


Figure 68: Frequency spectrum of grid voltage

2.2.6 Transfer function of the 3 Level converter

The semiconductor IGBT switches create some delay into the phase voltages. In order to tune the current controller this delay has to be considered with the transfer function of the LCL filter. First of all, the reference sinusoidal signal and the phase A voltage output of the converter has been superimposed on one another, then the delay between them has been measured shown in Figure 68.

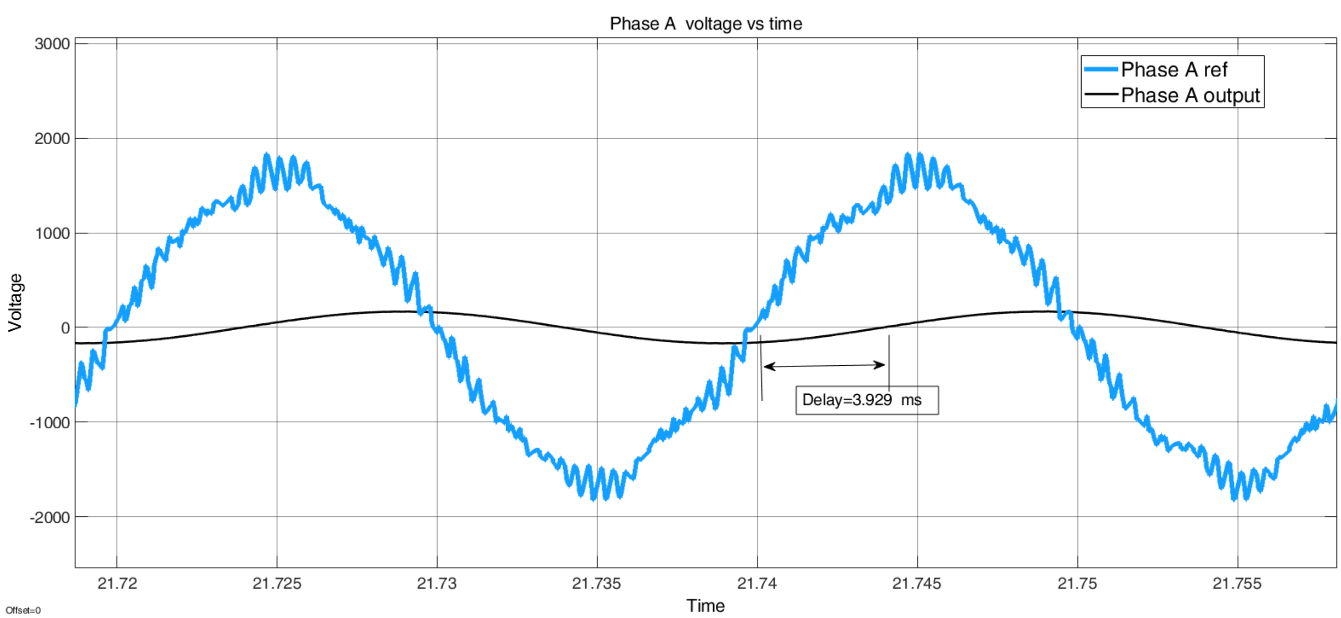


Figure 69: Phase A voltage delay measurement

The delay that has been measured is 3.929 ms. So, the transfer function of the converter is-

$$TF_{Con} = e^{-3.9e-3s}$$

2.3 Controller design

The basic things those have to be considered in order to design the inner current control loop are transfer function calculation and the corresponding controller parameter calculations. For controlling the current the widely used PI controller has been implemented here. In the first part of this section the advantages of dq over αβ reference frame while designing the controller part has been explained, next Kp and Ki values calculation has been shown.

Advantages of dq over αβ frame

A control system can be designed in α–β coordinate frame if it satisfies some conditions. The particular conditions are the feedback acquisition system that has no delay meaning that the feedback signal is producing the same output current without any kind of errors or time delays. Additionally, the voltage actuator is behaving as an ideal source that has no delay. [1]

Practically, the whole feedback system has some sort of delays, noises and unmodeled dynamics. As a result of this behavior the system has some phase and amplitude errors. Because of phase and amplitude errors the injected active and reactive power would not be at the desired values. Therefore, it is essential to convert the PI controllers in the dq frame instead of α–β frame. [1]

2.3.1 Determination of Kp ,Ki,Kd values

Step 1:

Formulation of the transfer function from mathematical equation.

Step 2:

Plotting of the transfer function by using matlab command sisotool.

Step 3:

Putting the controller tuning specifications in the controller plot.

Step 4:

Opening the tuning method from control system designer app.

Step 5:

Choosing of the controller type and calibrate the values and observe the nature of the response.

Step 6:

Once the desired output is found then the corresponding controller parameter is noted down and put in the controller to check the performance.

2.3.2 Inner current controller design

Refer to section 1.2.2 Generator controller the relation between the inner loop and outer loop has been explained in details. In this section the inner current loop has been explained in details. The whole procedures mentioned above have been implemented according to their phases. First of all the Simulink model to simulate the current controller has been explained, then the sample code to determine the transfer function has been shown, then the controller parameter realization from the step response has been elucidated. Finally, the output of the current controller has been shown.

Simulink model:

The Simulink model to design the current controller has been shown below in Figure 69.In this diagram the reference currents are coming from the set mentioned as I_dq_ref. The grid current has been measured and transformed from abc to dq in the left side mentioned as I_dq_measured and sent to the PI controllers. The output of the PI controller has been sent to the dq to abc back transformation block and then to the PWM generation block.

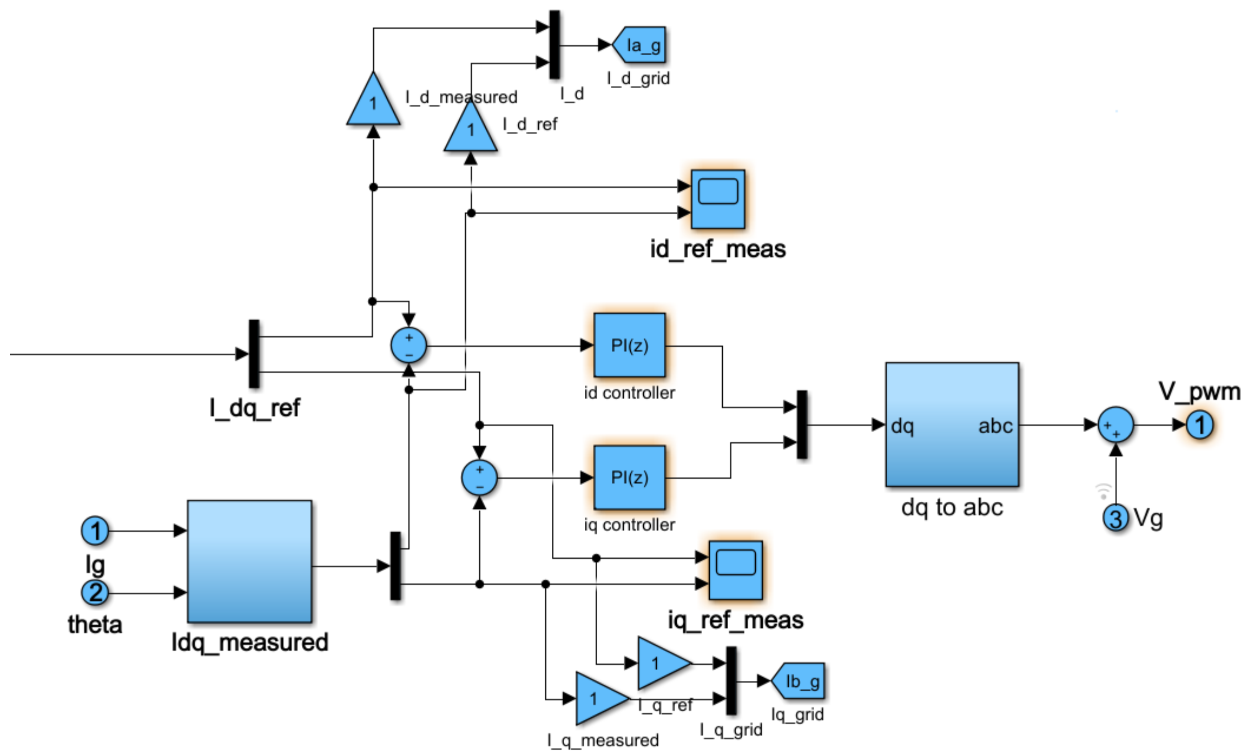


Figure 70:id,id controller simulink block

LCL filter controller tuning:

Step 1:

From mathematical calculation the transfer function of the current controller loop is:

$$TF_{LCL(open\ loop)} = \frac{R_1 * C_1 * s + 1}{L_1 * L_2 * C_1 * s^3 + (L_1 + L_2) * C_1 * R_1 * s^2 + (L_1 + L_2) * s}$$

Where,

R1=damping resistance,

C1=filter capacitance,

L1, L2=filter inductances,

<u>Sample matlab code to formulate the transfer function in the command window:</u>

```
%% LCL filter parameter
L2= 1.56e-04;
L1=1.6162e-04;
```

```
C1=2.89e-04;
R1=1;

%pi controller parameter of lcl filter
kp_lcl=14.55;
kd_lcl=6.1e-4;

%transfer function of LCL filter with damping resistance
num_lcl=[R1.*C1 1];
den_lcl=[L1.*L2.*C1 (L1+L2).*C1.*R1 (L1+L2) 0];
tf_lcl=tf(num_lcl,den_lcl);
```

Output:

tf_lcl =

```
          0.000289 s + 1
  --------------------------------------------
  7.286e-12 s^3 + 9.179e-08 s^2 + 0.0003176 s
```

Step 2:

The transfer function is run in the matlab command window. Next,a matlab command to call the sisotool is executed in the command window.

Sisotool(tf_lcl)

Step 3:

When the command is executed then a step plot will be appeared in a new window shown in Figure 5.In that window the bode plot and root locus plot will also appear along with it but only the step plot is considered. The mouse cursor is put in step plot and the right button is clicked, a new option will be

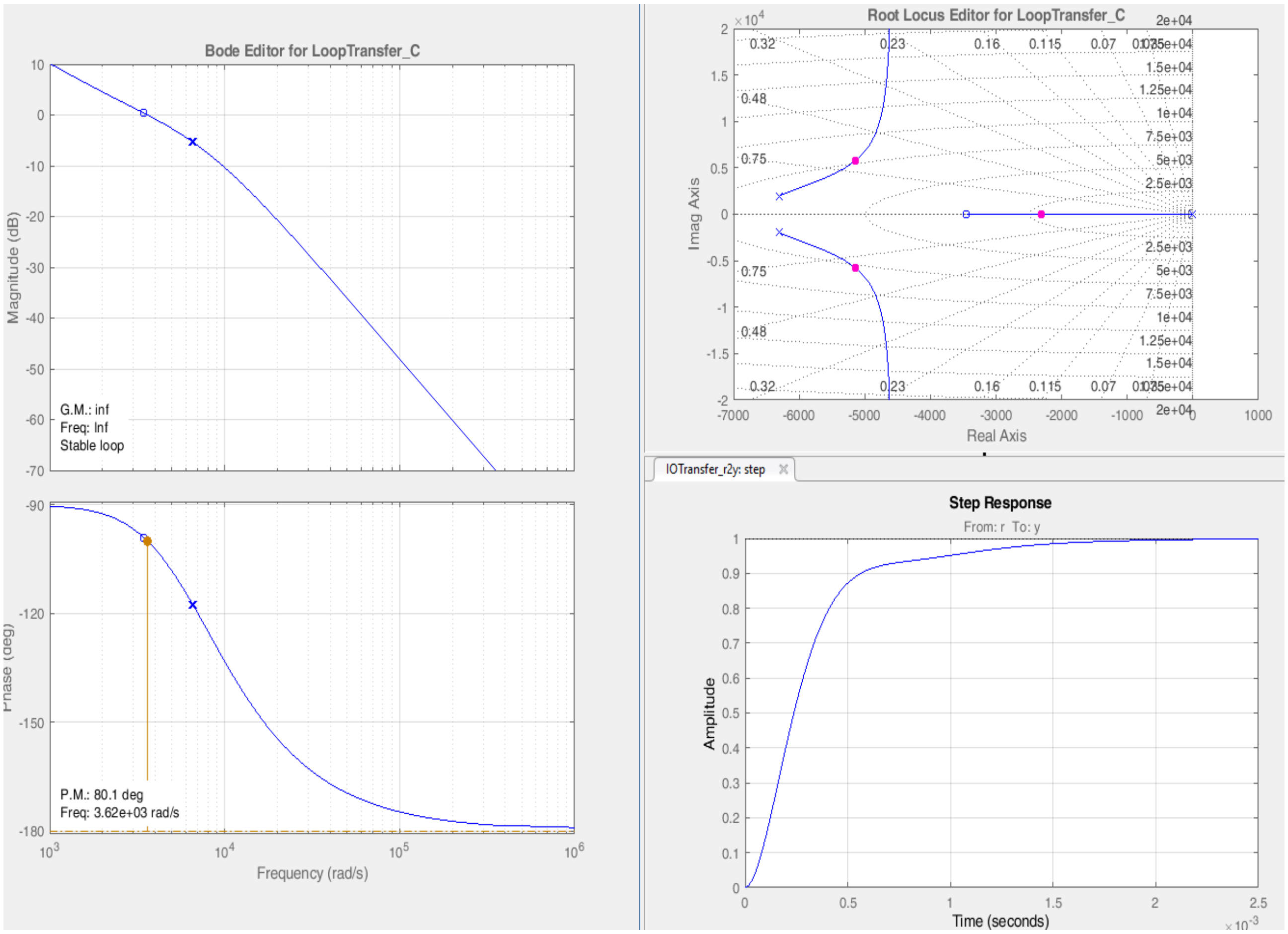


Figure 71: step plot of transfer function

Visible shown in Figure 6.In those options ,,design requirement'' is chosen and from that the ,,new'' option is also selected. When the new option is clicked with the left button of the mouse then a new window appears shown in Figure 7.In this window the controller specification is entered. For this case the corresponding parameter are mentioned in table below:

Table 11: LCL filter current controller parameter specification

Parameter name	Parameter value
Settling time	5e-3 seconds
Rise time	1e-3 seconds
Overshoot	10%

Step 4:

By clicking the pid tuning option, the pid tuner option has been brought to front.

Step 5:

In this step the controller tuning process is explained. For this case the pd controller has been chosen since if the pi controller is used then the integrator brings the overshoot above 10%.So, the integral term is avoided here. On the other hand the controller must respond before 5ms otherwise there lies a steady state error in the system. Therefore, the proportional term is increased at such value that the controller tracks the reference value at ms level.

In order to remove the overshoot term, the differential controller has been integrated with the proportional controller. The corresponding output has been shown in Figure 71 & Figure 72 respectively.

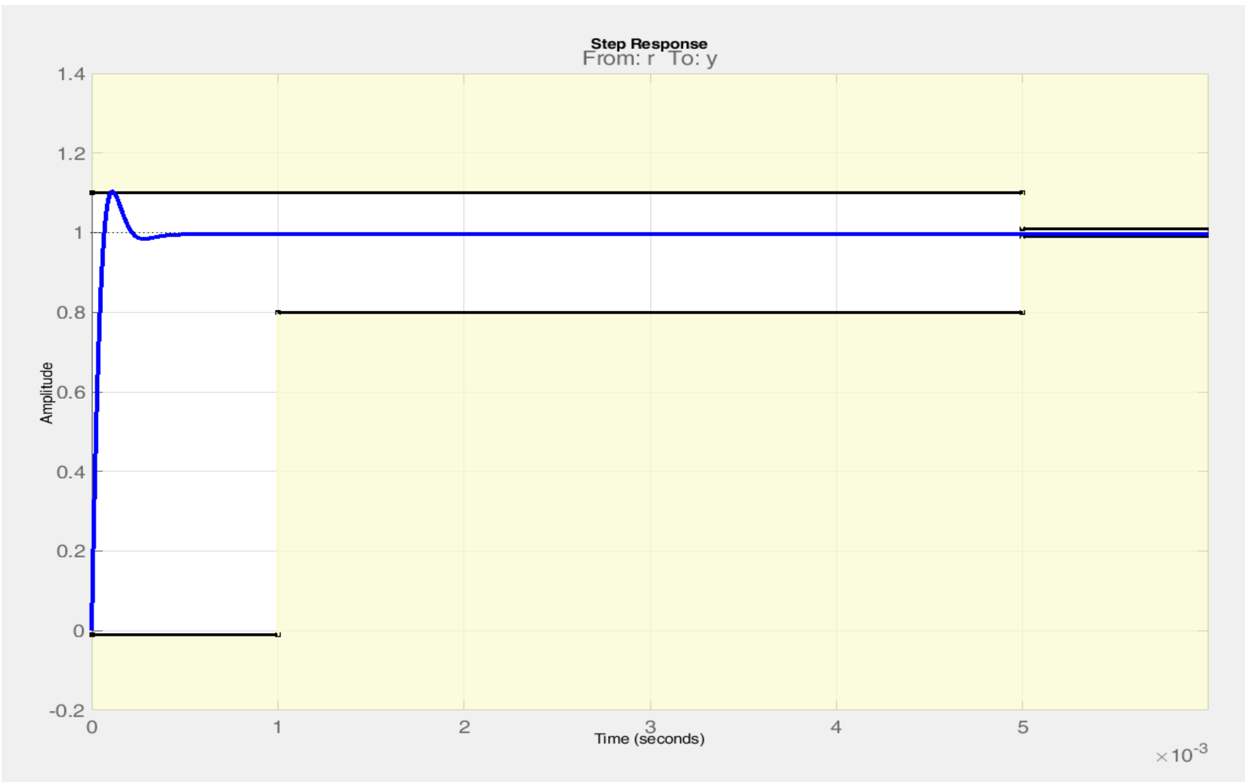


Figure 72: controller calibration

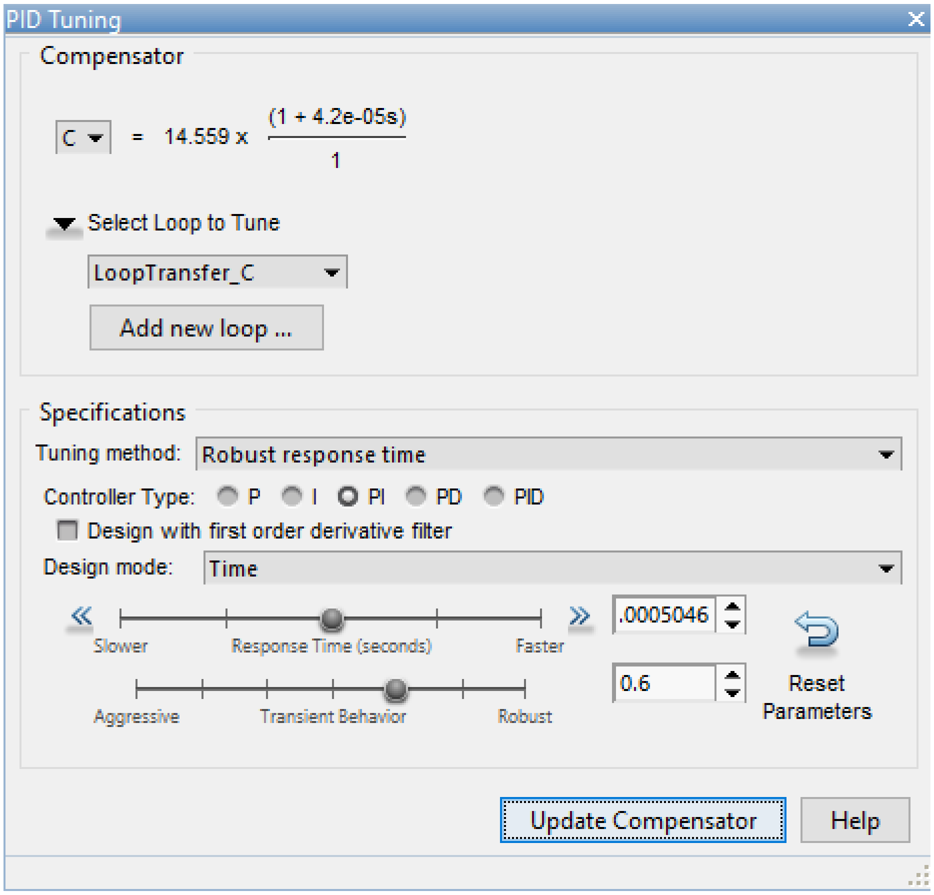


Figure 73: Calibrated output of controller

Step 6:

When the controller is adjusted according to the requirement and put the step response in the white region, then the value of the compensator, C shown in Figure 72 is noted down and put the value in model to see the effect.

After adjusting the controllers the corresponding value shown below:

Figure 74: LCL filter controller parameter

Parameter name	value
Proportional gain,kp_lcl	14.559
Derivative gain,kd_lcl	6.11e-5

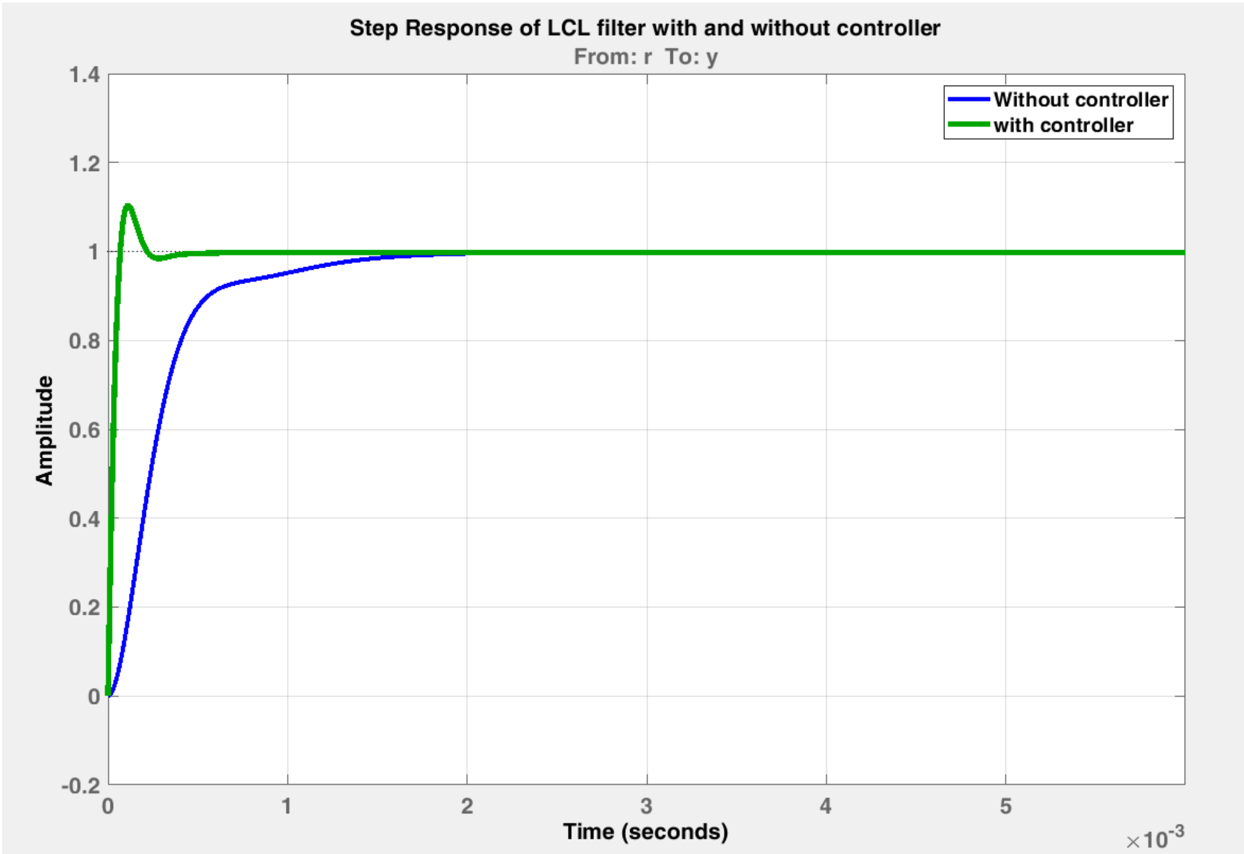


Figure 75: Step response of LCL filter with and without controller

Simulation result:

In order to simulate the current controllers the following parameters shown in Table 12 have been considered.

Table 12: Simulation parameter for lcl current controller

Parameter name	Parameter value
Id reference	1000 Ampere
Iq reference	-2200Ampere
Proportional gain,Kp_lcl	14.55
Differential gain,Kd_lcl	6.11e-4

The inner current controller has been divided into two parts: id & iq. The reference values for the id and iq current are set 1000 and -2200 respectively shown in the figures below. After putting the values of Kp and Ki in the controller the current controlled loop has the desired performance shown in Figure 75 & Figure 76 respectively.

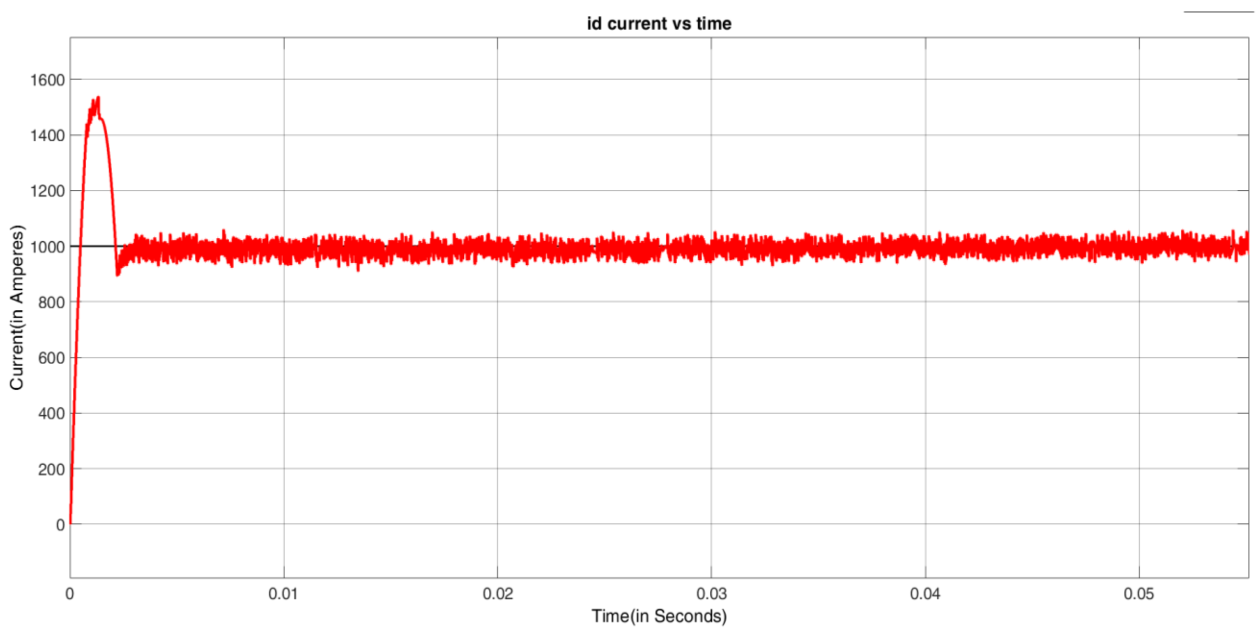


Figure 76: id current vs time

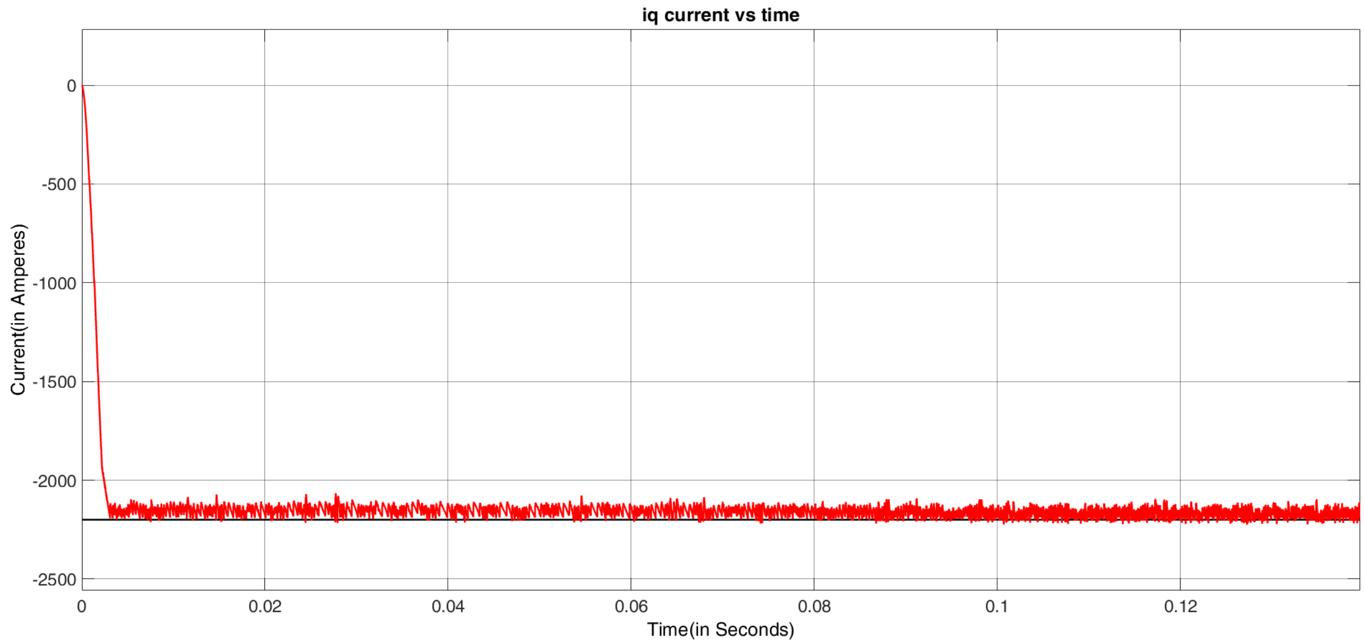


Figure 77: iq current vs time

2.3.3 Outer loop design

The inner current loop can be implemented to control the current inside the grid side converter. However, there are some other parameters those can be controlled in conjunction to the inner current loop. These parameters are controlled in an outer loop. The outer loop parameters those can be controlled are mentioned below:

a) DC link voltage (Vdc) & Reactive power control (Q): In this mode only these two parameters are controlled. The rest of the parameters like P control, power factor control are deactivated.

b) id, iq control(reference from the machine side converter reference): The wind generator generates id and iq current in the stator. In this mode this same current is flowed into the grid side id and iq controller so that the generated power could be injected to the grid without charging the capacitor mostly. The power factor mode will not work in this mode.

c) Real power (P) & Reactive power (Q) control: In this mode the real power and reactive powers are controlled. They both could be given manually inside the diagram in the dialog section. However, the power factor can be given directly. The power factor can be controlled only in this mode.

There is a relationship between the inner and outer loop for controlling. The outer loop generates the reference current id, iq for the inner current controlled loop. The inner loop takes the references values from the outer loop and compares them with the feedback values and hence flows the same current as of the outer loop reference. The outer loop parameters can be controlled only one couple at a time. For example as mentioned above if option a is chosen to control then the other two options can't be controlled.

In this thesis model for controlling the outer loop parameters a typical block diagram has been designed shown in Figure 77.As mentioned in the figure below each of the options mentioned above has been defined by cases: Case 1= DC link voltage (Vdc) & Reactive power control (Q), case 2= id,iq control(reference from the machine side converter reference), case 3= Real power (P) & Reactive power (Q) control.

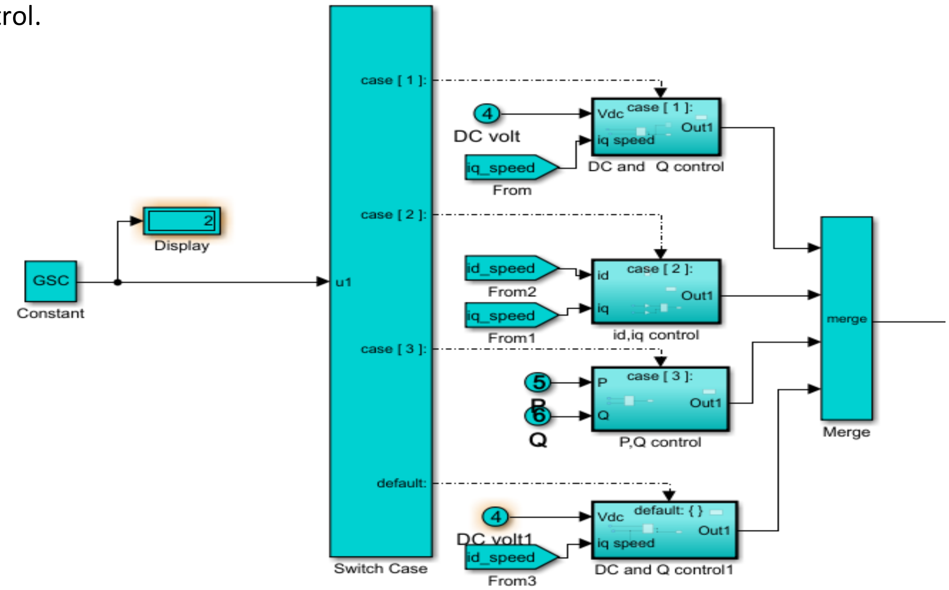


Figure 78 : Outer loop control block diagram

2.3.4 DC link voltage control:

In this section first of all the transfer of the voltage control loop and reactive power control loop have been calculated and then the step response of the closed loop transfer function has been plotted. From the step response of the closed loop transfer function the PI controller values have been found by using the MATLAB sisotool apps.

Transfer function calculation:

The Kirchhoff's current law states that the phasor sum of the current entering in a node is equal to the phasor sum of the currents leaving the node. In the grid side converter section, the current that is coming from the generator side is defined as i_dcs, the capacitor charging current is mentioned as ic, the grid side current is defined as i_dcg. The generator current is entering to this node but the other two currents are leaving this node. According to this law shown in Figure 78,

$$i_c = i_{dcs} - i_{dcg}$$

$$=> C\frac{dV_C}{dt} = -i_{dcg} + i_{dcs} \qquad (19)$$

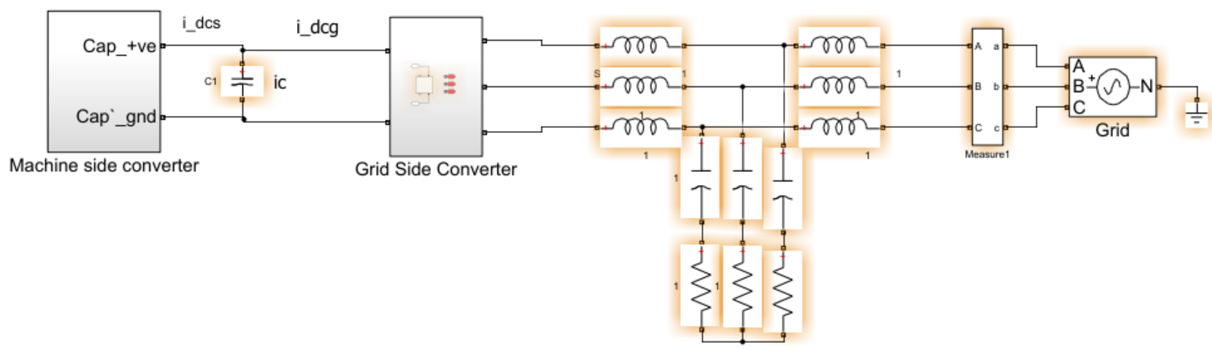


Figure 79: Equivalent model of a Grid connected system

Where,

i_c=Current going through the capacitor.

i_{dcg}=Current passing through the grid side converter.

i_{dcs}=Current coming from the machine side converter.

V_c=Voltage across the capacitor.

C=Capacitance of the capacitor.

,,Tellegen's Theorem can be stated as , in any linear, nonlinear, passive, active, time variant or time invariant network the summation of power (instantaneous or complex power of sources) is zero.'' [30]

By considering the power balance theorem mentioned above,

$$V_c * i_{dcg} = \frac{3}{2} * V_d * i_d \qquad (20)$$

Where,

Vc=Voltage across the capacitor, i_{dcg}=Current passing through the grid side converter, V_d=d axis voltage of grid, id=d axis current of grid

Putting the values of i_{dcg} from equation 21 in equation 20 we get,

$$\frac{dV_c}{dt} = -\frac{3}{2} * V_d * i_d * \frac{1}{V_c} * \frac{1}{C} + i_{dcs} * \frac{1}{C}$$

$$=> dV_c = -\frac{3}{2} * V_d * i_d * \frac{1}{V_c} * \frac{1}{C} * dt + i_{dcs} * \frac{1}{C} * dt$$

At around the nonlinear dynamics could be linearized as-

$$=> dV_c = -\frac{3}{2} * V_d * i_d * \frac{1}{V_c} * \frac{1}{C} * \frac{1}{s} + i_{dcs} * \frac{1}{s * C} \tag{21}$$

In the equation above the second term is neglected since the input term is related to the first term and the second term will be cross coupled in the controller design. The system that is being considered consists the input id current and the output dc link voltage, Vc-

Hence, from the equation (21) the open loop transfer function can be found as-

$$tf_{open\ loop\ (dclink)} = \frac{Vc^2}{i_d^*} = -\frac{3}{2} * V_d * \frac{1}{C * s} * \frac{1}{(T_{cl} \ * s + 1)} \tag{22}$$

Where,

$T_{cl} = \frac{T_s}{2} + T_{delay} = delay\ of\ the\ whole\ system$

T_s=Switching time.

T_{delay}=Converter time delay.

$\frac{i_d}{i_d^*} = \frac{i_q}{i_q^*} = \frac{1}{T_{cl} * s + 1}$ [31]

Simulink block diagram:

The dc link voltage control loop is shown in Figure 79.The reference signal is compared with the measured output through a square block. The reason to use a square block is because in equation 22(the transfer function equation) there is square in the output voltage and also a minus sign. The minus sign is included in the loop below in the end of id reference current.

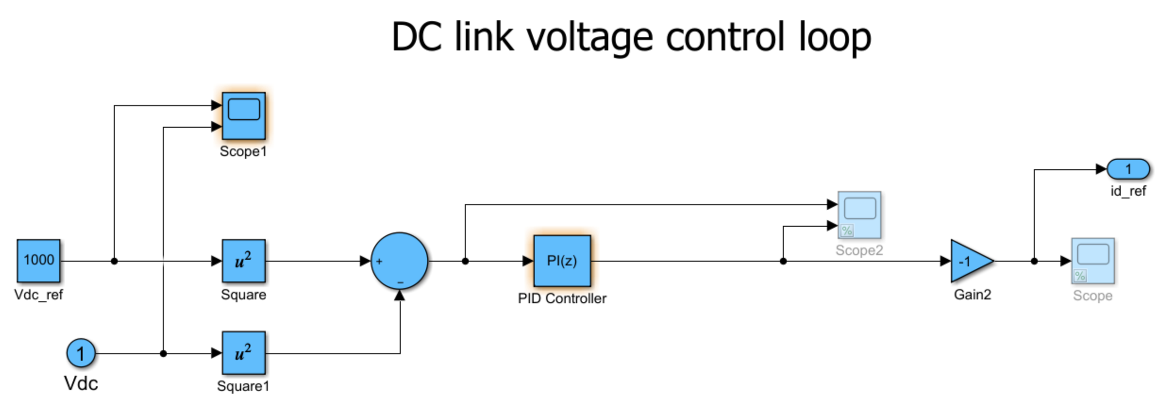


Figure 80: DC link voltage control loop

Dc link voltage controller tuning:

Step 1:

From mathematical calculation the transfer function of the current controller loop is:

$$Ttf_{open\ loop\ (dclink)} = \frac{Vc^2}{i_d^*} = -\frac{3}{2} * V_d * \frac{1}{C * s} * \frac{1}{(T_{cl} \ * s + 1)}$$

Where,

I_d=d axis current of grid,

V_d=d axis voltage of the grid,

C=capacitance of the dc link capacitor.

V_c=Voltage across the capacitor.

Tcl=Total delay of the system.

Sample matlab code to formulate the transfer function in the command window:

```
%% trasnfer function of dc link voltage controller
%pd controller parameter of dc link
kp_dc=1.57;
kd_dc=5.67e-3;
%parameter of dc link voltage loop
Ts=1/(2*fc);
Td=2*3.9e-3;
Tt=Ts+Td;
Vd=563;
C=.5; %DC link capacitance
% delay transfer function
num_delay=[1]
den_delay=[Tt 1]
tf_delay=tf(num_delay,den_delay);
%dc voltage transfer fucntion without delay part
num_dc=[1.5*Vd]
den_dc=[C 0]
tf_dc=tf(num_dc,den_dc);
%total transfer function
tf_dv=tf_dc*tf_delay
```

Output:

```
tf_dv =

         844.5
  -----------------
  0.004 s^2 + 0.5 s
```

Step 2:

The transfer function is run in the matlab command window. Next,a matlab command to call the sisotool is executed in the command window.

Sisotool(tf_dv)

Step 3:

The step plot is shown in Figure 5.

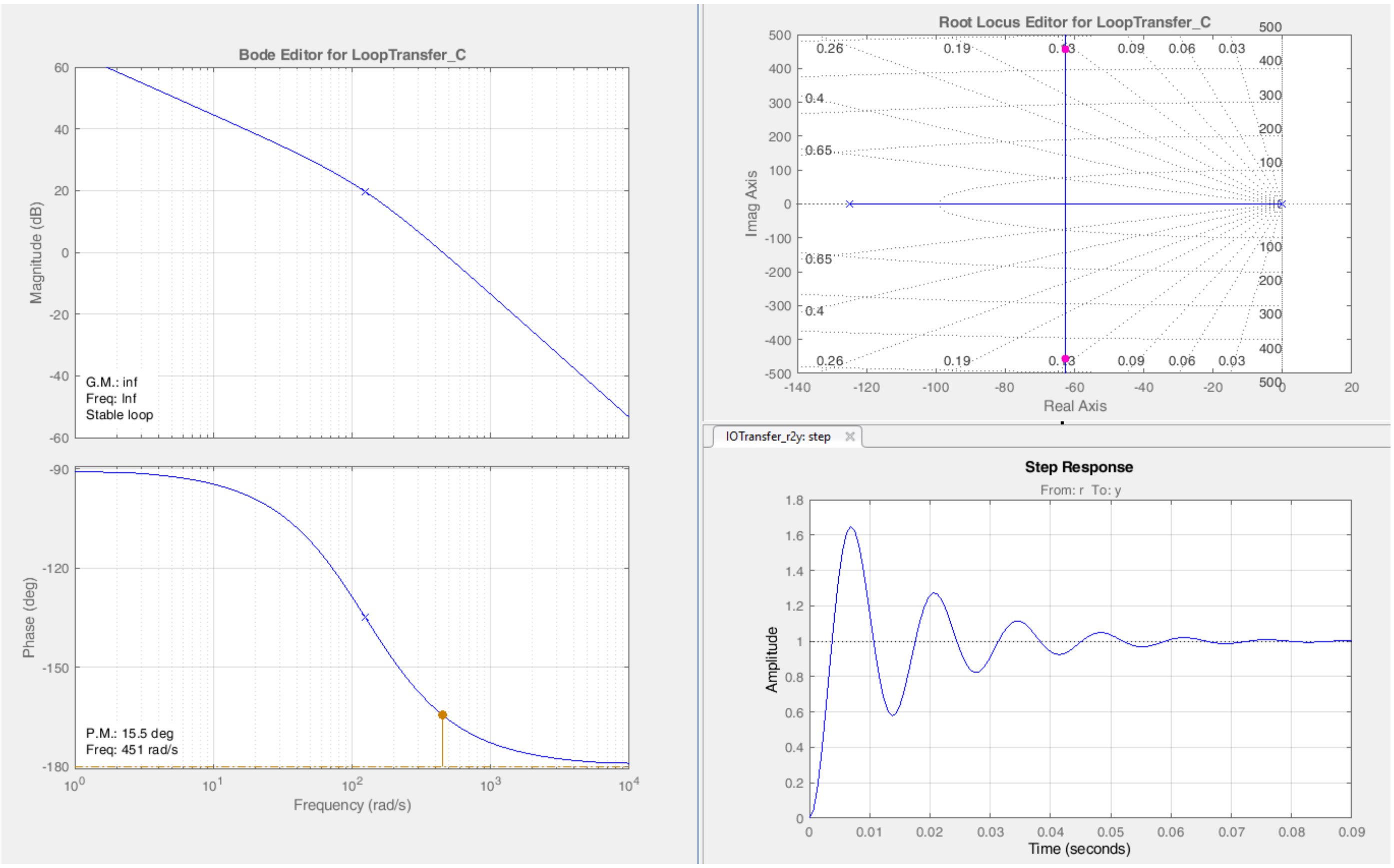


Figure 81: step plot of transfer function

The corresponding specification data for tuning the controller is mentioned in Table 13.

Table 13: PMSG torque controller parameter specification

Parameter name	Parameter value
Settling time	2e-3 seconds
Rise time	8e-3 seconds
Overshoot	10%

Step 4:

By clicking the pid tuning option, the pid tuner option has been brought to front.

Step 5:

In this step the controller tuning process is explained. For this case the pd controller has been chosen since if the pi controller is used then the integrator brings the overshoot above 10%.So, the integral term is avoided here. The proportional gain need not to increase too much since the step response is already lies with zero steady state error.

In order to remove the overshoot term, the differential controller has been integrated with the proportional controller. The corresponding output has been shown in Figure 71 & Figure 72

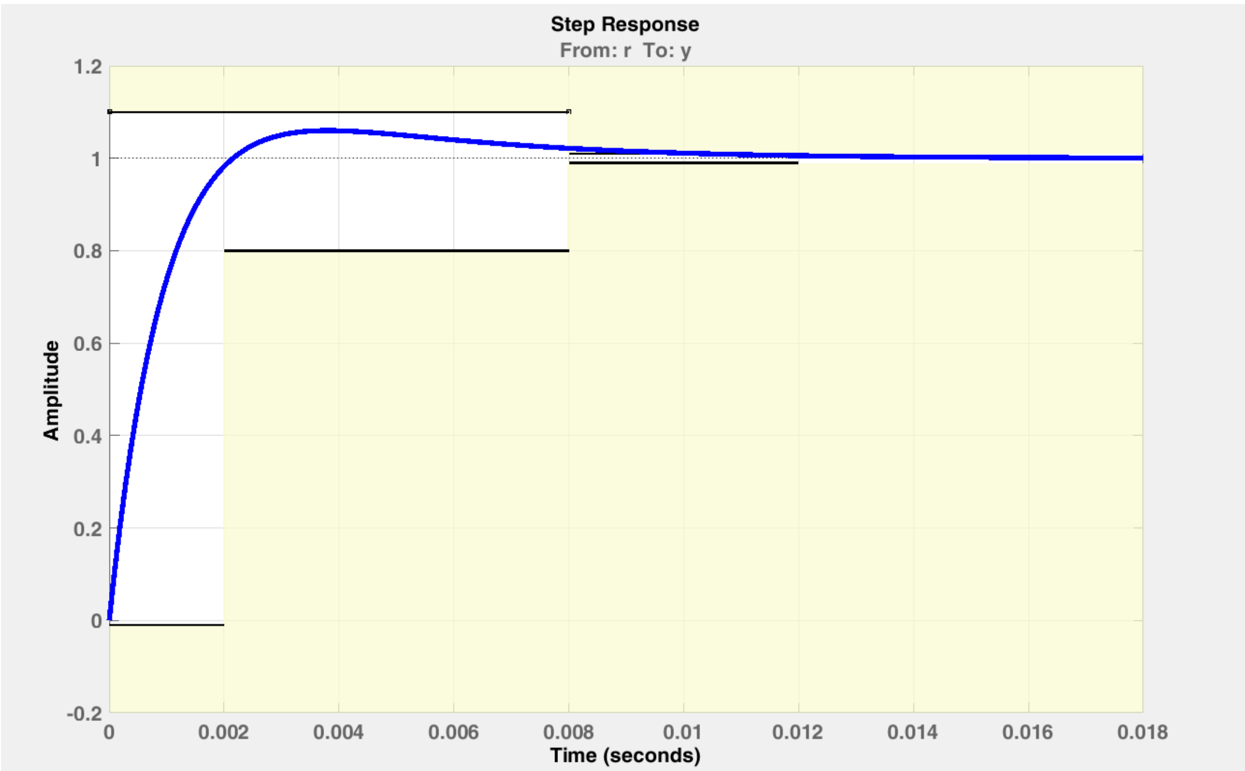


Figure 82: controller calibration

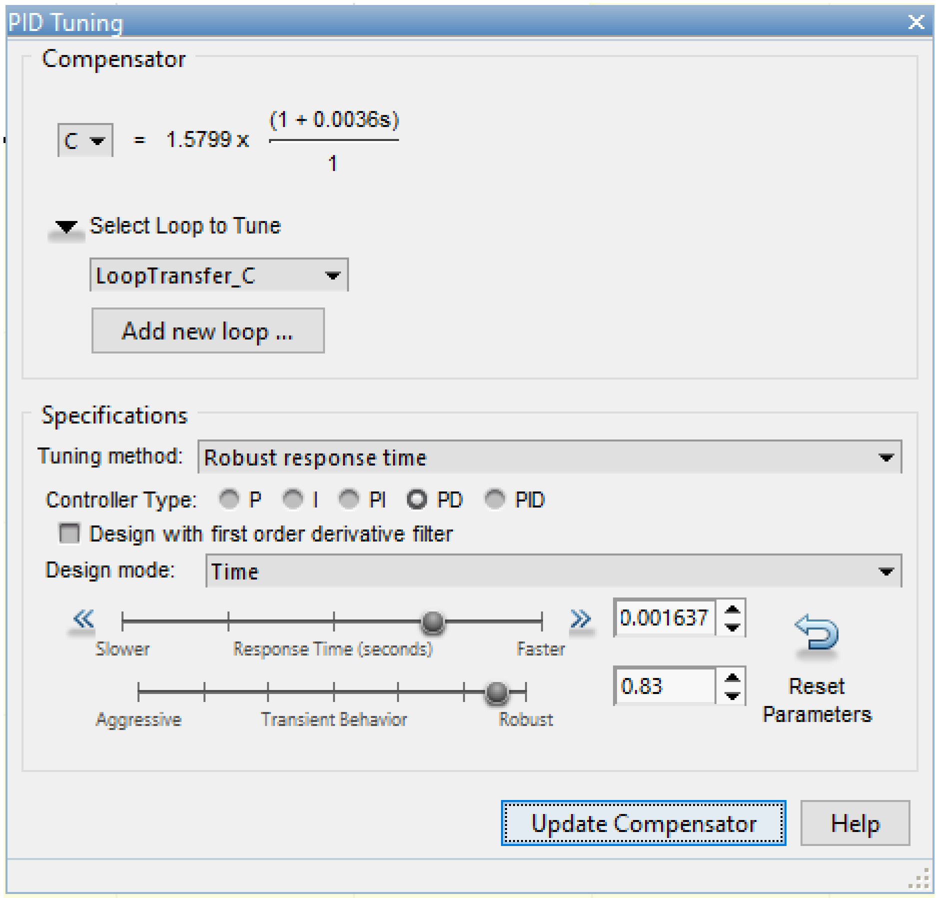


Figure 83: Calibrated output of controller

Step 6:

When the controller is adjusted according to the requirement and put the step response in the white region, then the value of the compensator, C shown in Figure 72 is noted down and put the value in model to see the effect.

After adjusting the controllers the corresponding value shown below:

Figure 84: LCL filter controller parameter

Parameter name	value
Proportional gain,kp_lcl	1.57
Derivative gain,kd_lcl	5.65e-3

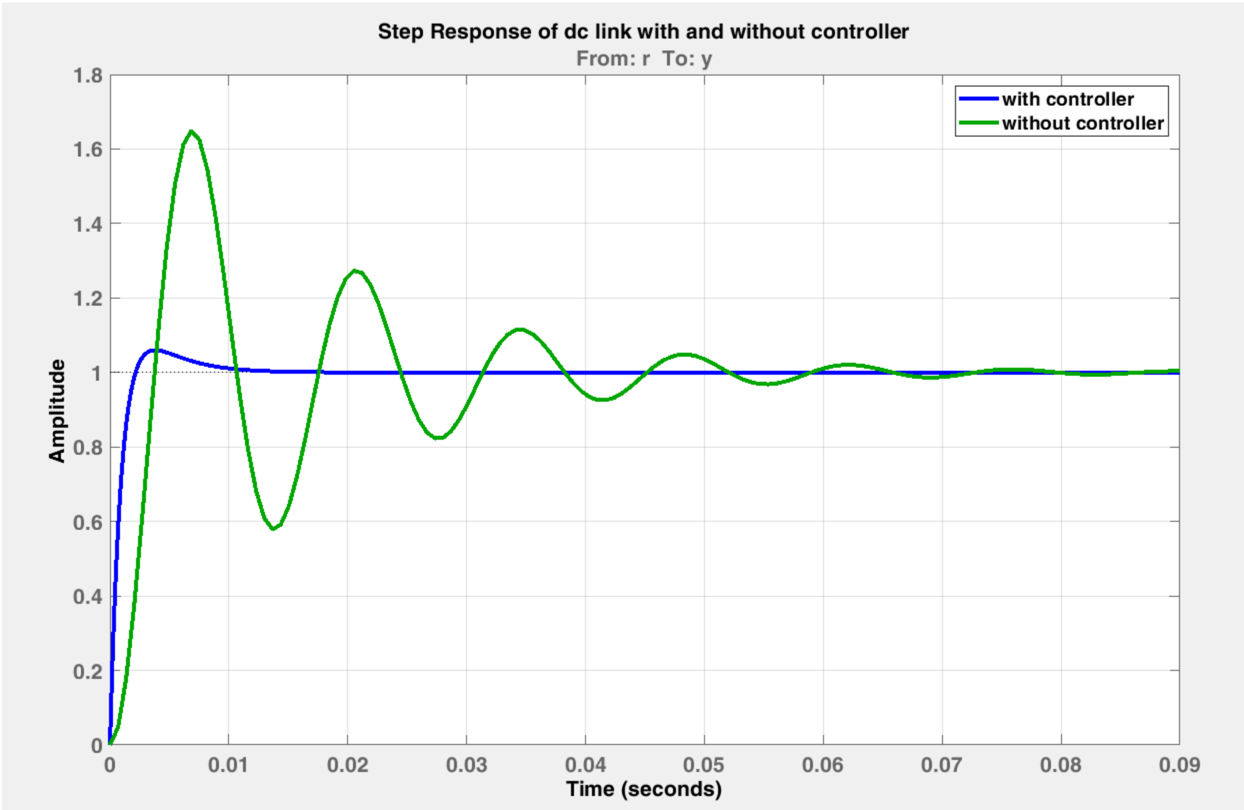


Figure 85: DC link voltage controller output with and without controller

The step response of the dc link voltage controller with and without controller is shown in Figure 3.

Simulation result:

In order to simulate the behavior of the dc link voltage controller the following parameter shown in table 1 has been considered:

Parameter name	Parameter value
DC link voltage reference,Vdc_ref	1217V
Proportional gain,Kp_dc	1.57
Derivative gain,Kd_dc	5.67e-3

The simulation result of the dc link voltage controller has been shown in figure 84 below.

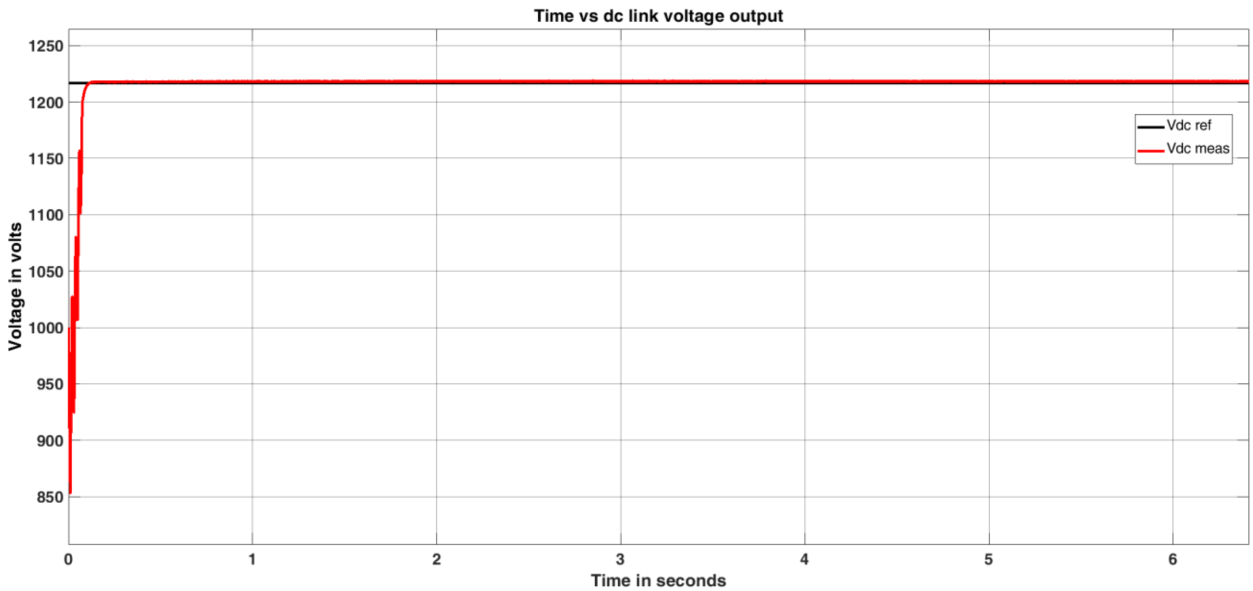


Figure 86: DC link voltage vs time

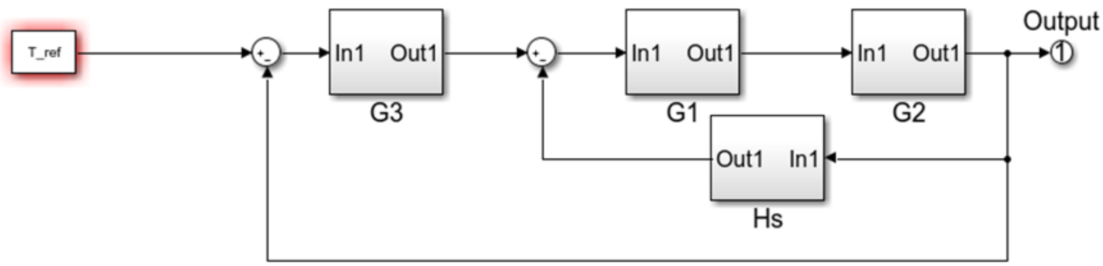
2.3.5 Reactive power Q control

In this section first of all the transfer function for the Q controller has been calculated and then corresponding step plot of the open loop transfer function has been shown. From the step plot the corresponding controller parameter has been calculated. Finally, the response of the calculated parameter has been used to see the performance of the reactive power control system.

Transfer function of Q control loop

Q loop transfer function:

The block diagram reduction technique for the Q loop has been shown in figure 2 below. In the figure the plant transfer function consists of the current controller of the grid side and the transfer function of the LCL filter. The upper diagram has been reduced to one single transfer function shown at the bottom side of Figure 86.



According to block diagram reduction technique:

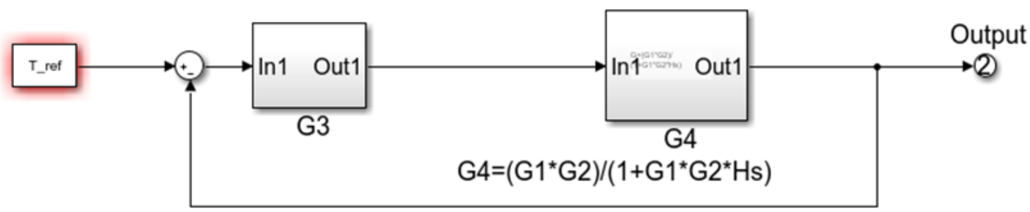


Figure 87: Block diagram reduction technique of Q controller

$$G2 = \frac{R_1 * C_1 * s + 1}{L_1 * L_2 * C_1 * s^3 + (L_1 + L_2) * C_1 * R_1 * s^2 + (L_1 + L_2) * s}$$

$$G1 = K_p + s * K_d$$

$$Hs = 1$$

Here,

G1=Current controller transfer function

G2=LCL filter transfer function.

Hs=feedback of current loop

G3=pi controller of torque control loop.

Kp =proportional gain of current controller

Ki=integral gain of current controller

R1=Filter resistance,C1=Filter capacitance,L1=Filter inductance

Therefore, the complete transfer function is-

$$G4 = \frac{(R_1 * C_1 * s + 1)(K_p + s * K_d)}{s * (L_1 * L_2 * C_1 * s^3 + (L_1 + L_2) * R_1 * C_1 * s^2 + (L_1 + L_2) * s) + (R_1 * C_1 * s) * (s * K_p + K_i)}$$

Q controller tuning:

Step 1:

From mathematical calculation the transfer function of the Q controller loop is:

$$tf\_q = \frac{(R_1 * C_1 * s + 1)(K_p + s * K_d)}{s * (L_1 * L_2 * C_1 * s^3 + (L_1 + L_2) * R_1 * C_1 * s^2 + (L_1 + L_2) * s) + (R_1 * C_1 * s) * (s * K_p + K_i)}$$

Where,

R1,C1,L1,L2=Filter resistance,capacitance,inductances.

Kp,Kd=PD controller proportional gain,differential gain.

<u>Sample matlab code to formulate the transfer function in the command window:</u>

```
%% LCL filter parameter
L2= 1.56e-04;
L1=1.6162e-04;
C1=2.89e-04;
R1=1;

%pi controller parameter of lcl filter
kp_lcl=14.55;
kd_lcl=6.11e-4;

%transfer function of LCL filter with damping resistance
num_lcl=[R1.*C1 1];
den_lcl=[L1.*L2.*C1 (L1+L2).*C1.*R1 (L1+L2) 0];
tf_lcl=tf(num_lcl,den_lcl);

%% Transfer function of the P & Q controller
%transfer function of PD current controller of LCL filter
num_q=[kd_lcl kp_lcl];
den_q=[1];
tf_pd=tf(num_q,den_q);

%total open loop transfer function of the P&Q controller
tf_q=feedback(tf_pd*tf_lcl,1);
```

Output:

tf_q =

```
    1.766e-07 s^2 + 0.004816 s + 14.55
  ---------------------------------------------------
  7.286e-12 s^3 + 2.684e-07 s^2 + 0.005134 s + 14.55
```

Step 2:

The transfer function is run in the matlab command window. Next,a matlab command to call the sisotool is executed in the command window.

Sisotool(tf_q)

Step 3:

The step plot is shown in Figure 5.

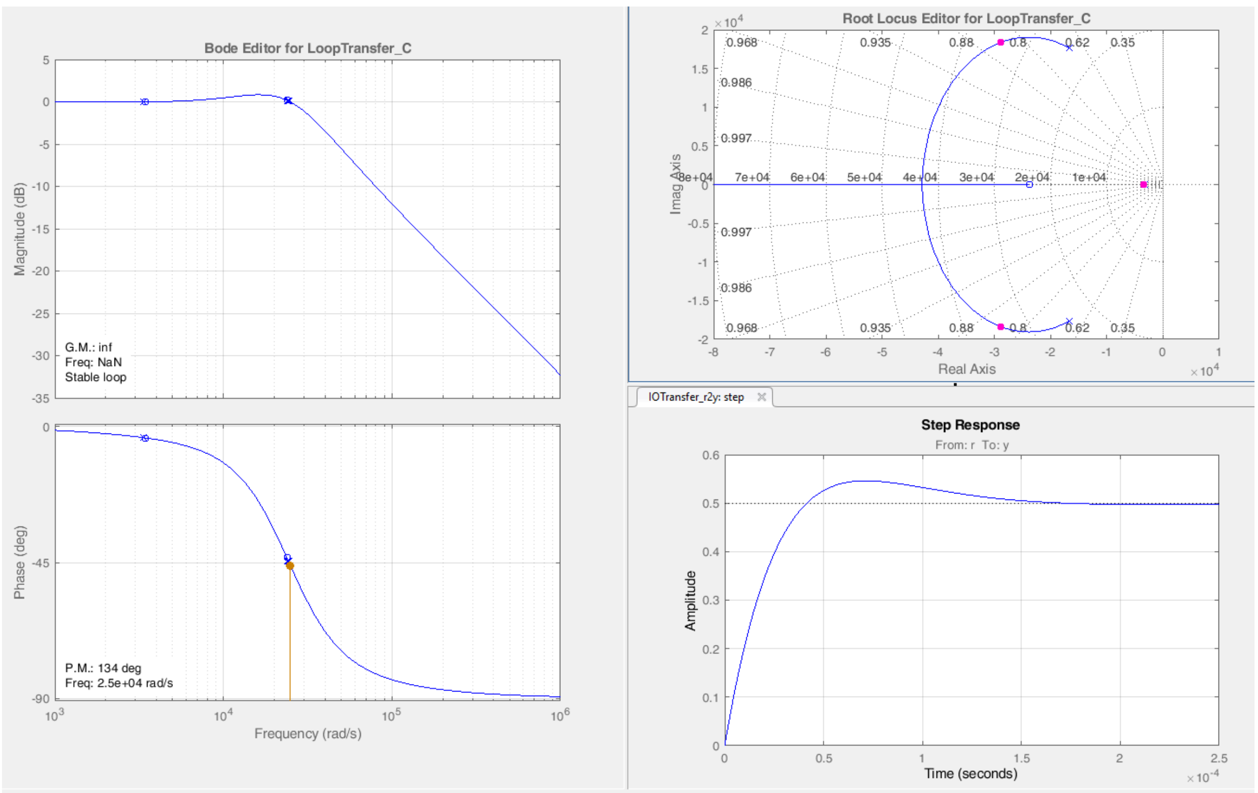


Figure 88: step plot of transfer function

The corresponding specification data for tuning the controller is mentioned in Table 13.The settling time and rise time has been considered high enough since if low response time particularly in ms range time is chosen then there are too much oscillation in the reference current of current controlled loop. However, if the response time or settling time is selected in 1-15 second range then the oscillation in the reference current dies out.The comparison between different response time is shown below:

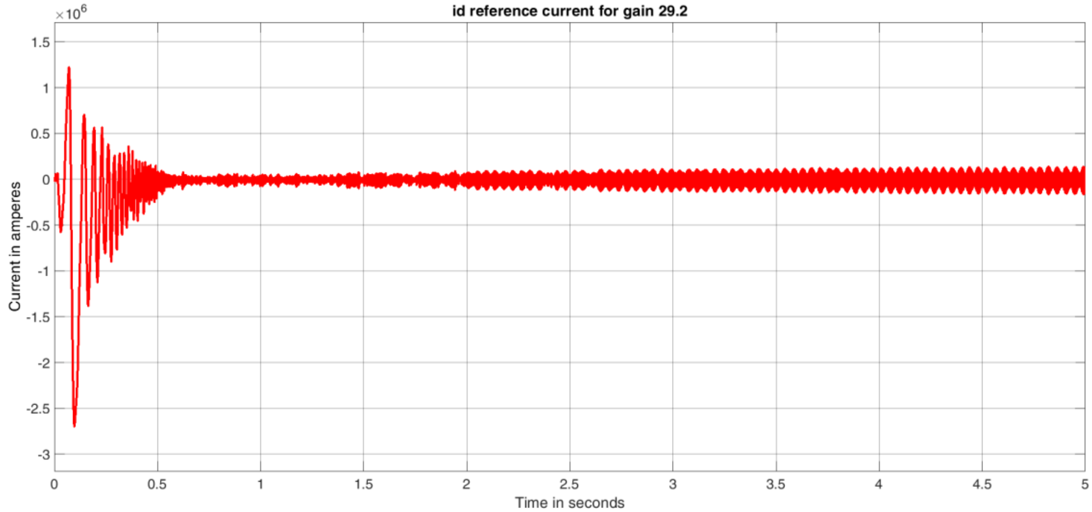


Figure 89: id current when response time is .0753s

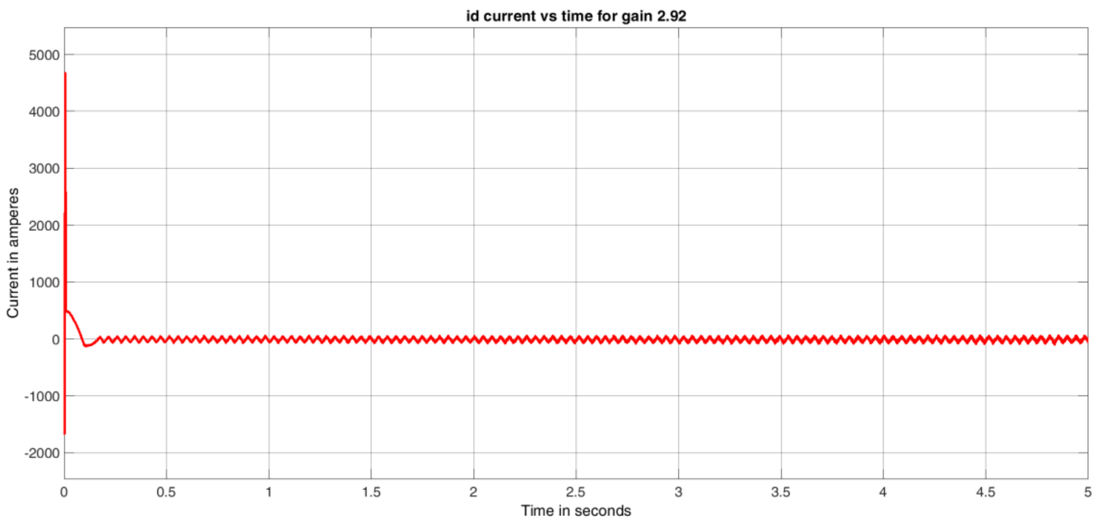


Figure 90: id current when response time is .753s

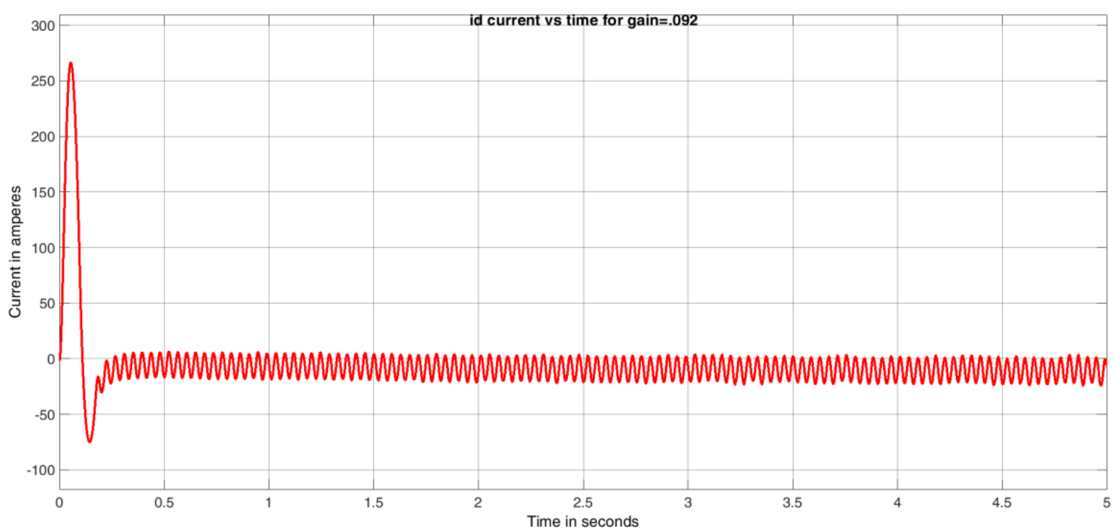


Figure 91:id current when response time is 7.53s

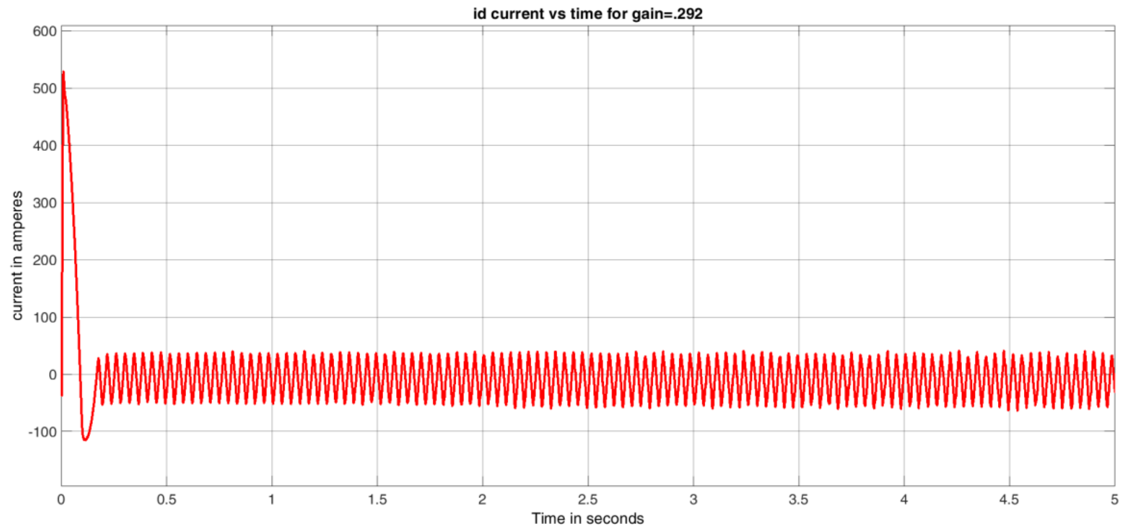


Figure 92:id current when response time is 75.3s

Table 14: Q controller parameter specification

Parameter name	Parameter value
Settling time	8 seconds
Rise time	14 seconds
Overshoot	10%

Step 4:

By clicking the pid tuning option, the pid tuner option has been brought to front.

Step 5:

In this step the controller tuning process is explained. For this case the Integral controller has been chosen since the proportional term becomes less dominant for boosting the current. Integral controller also improves the output satisfactorily. The corresponding output has been shown in Figure 92 & Figure 71

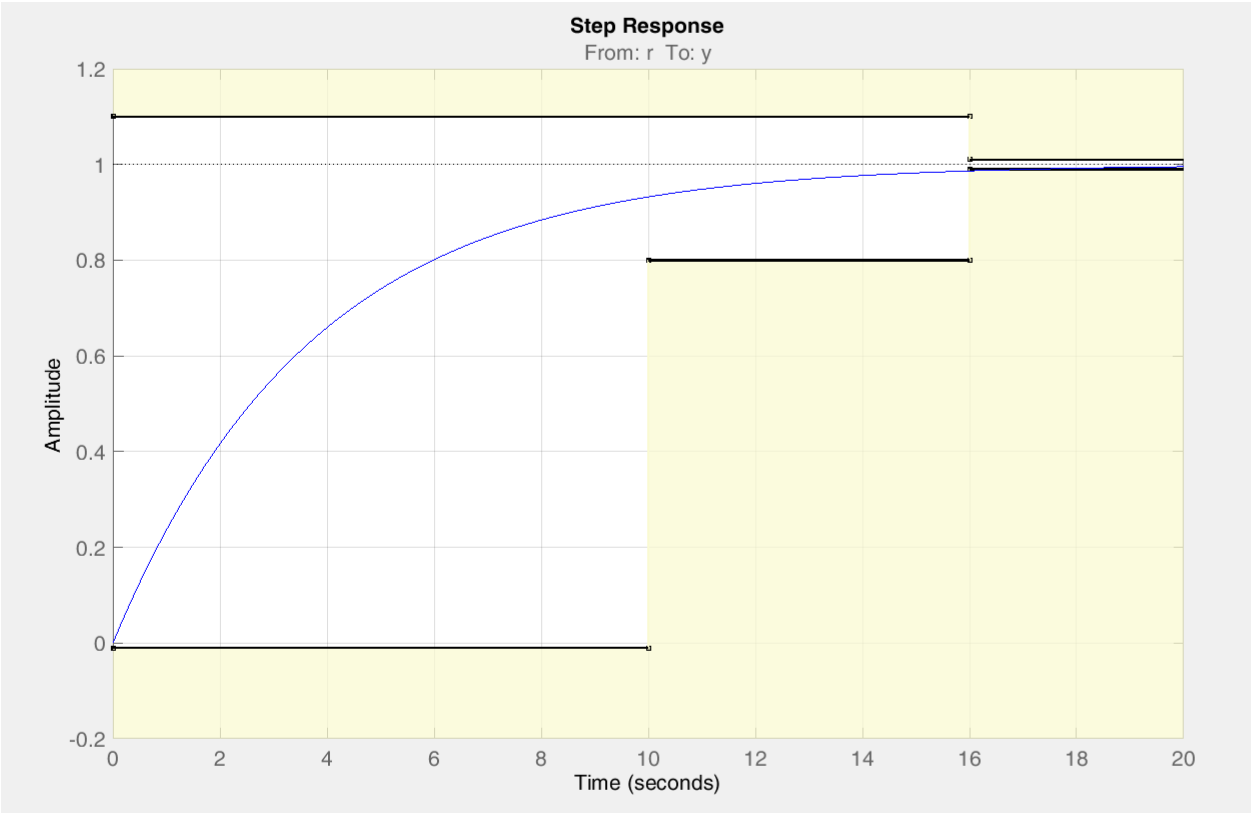


Figure 93: q controller calibration

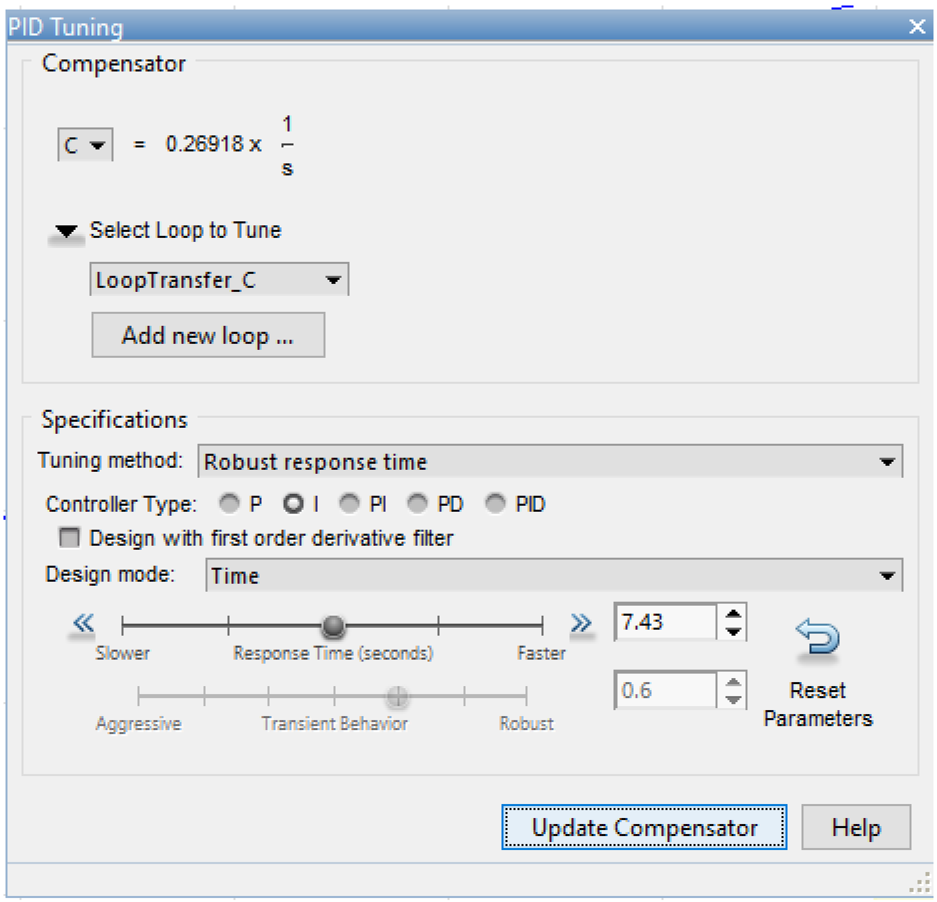


Figure 95: Calibrated output of controller

Step 6:

When the controller is adjusted according to the requirement and put the step response in the white region, then the value of the compensator, C shown in Figure 72 is noted down and put the value in model to see the effect.

After adjusting the controllers the corresponding value shown below:

Figure 96: LCL filter controller parameter

Parameter name	value
Integral gain,ki_lcl	0.269

Step response of Q loop transfer function

The step plot of the q control loop is shown below:

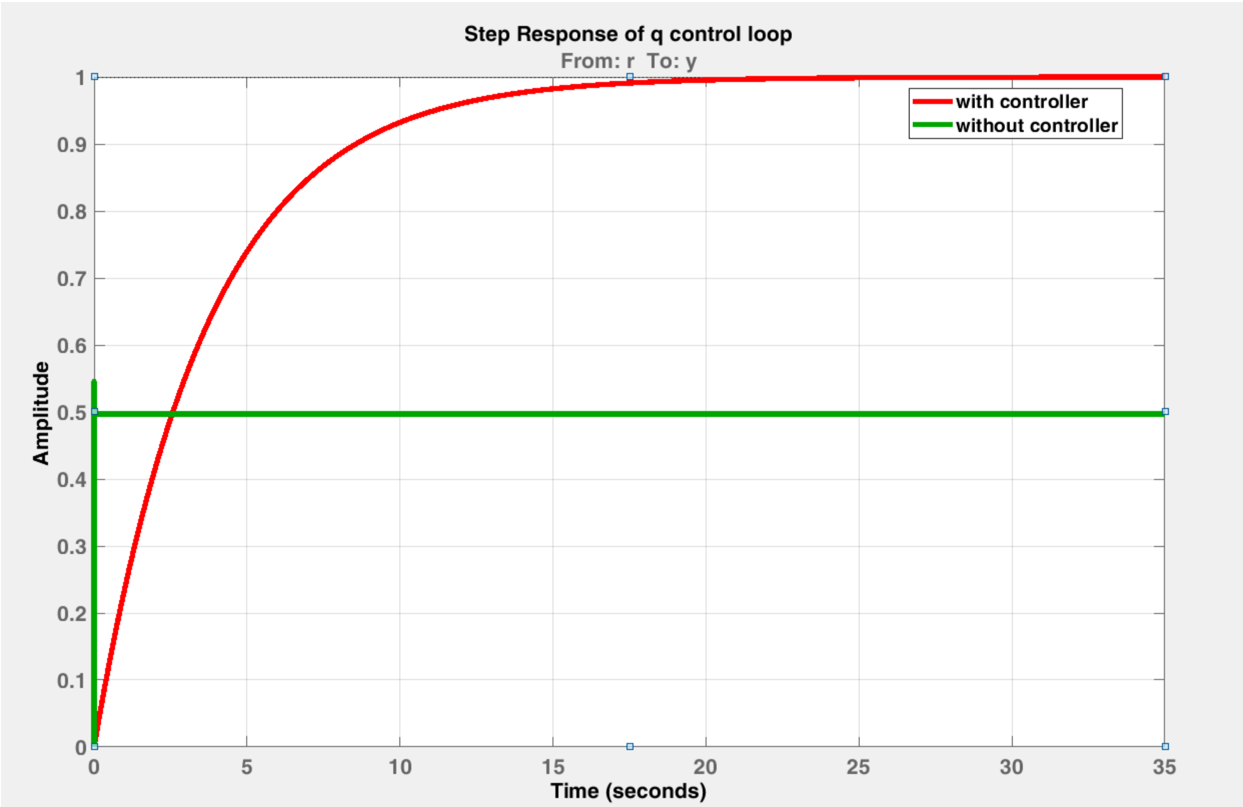


Figure 97 : Step response of Q loop

Output of the Q loop

In order to simulate the Q controller the parameters those are considered are mentioned below in the table below:

Table 15: Simulation parameter for q control loop

Parameter name	Parameter value
Q reference	0 MVar
Integral gain,Ki_q	0.269
Wind speed	12m/s

The controller parameter value found in the previous section has been put and the corresponding response is shown in Figure 97 [32].

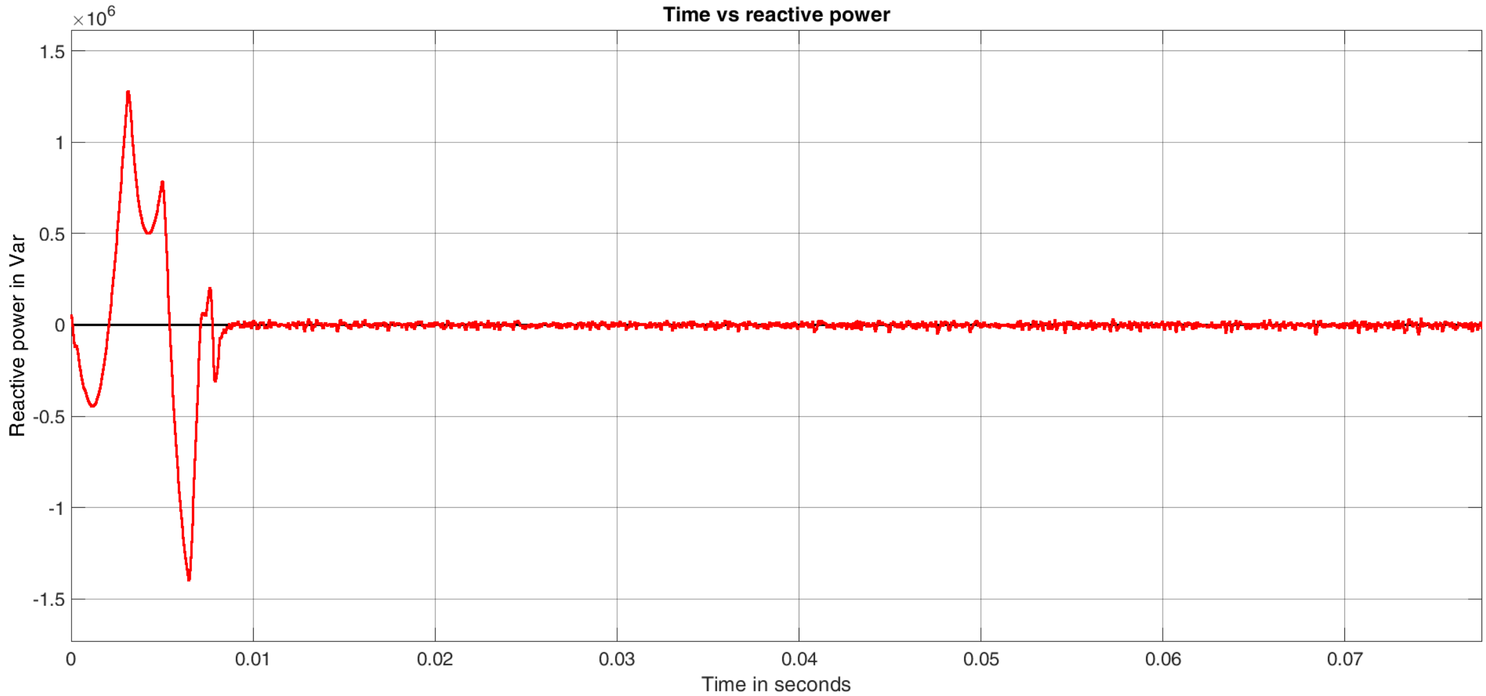


Figure 98: Time vs reactive power with controller

2.3.6 Real power, P control loop

The required transfer function to calculate the controller gain for this loop is the same as the Q control loop. The calculated PI controller value is also the same and has been implemented in the Integral controller for the P control loop. The output of the P control has been shown in Figure 98 below. The reference value has been set at 1.5 MW.

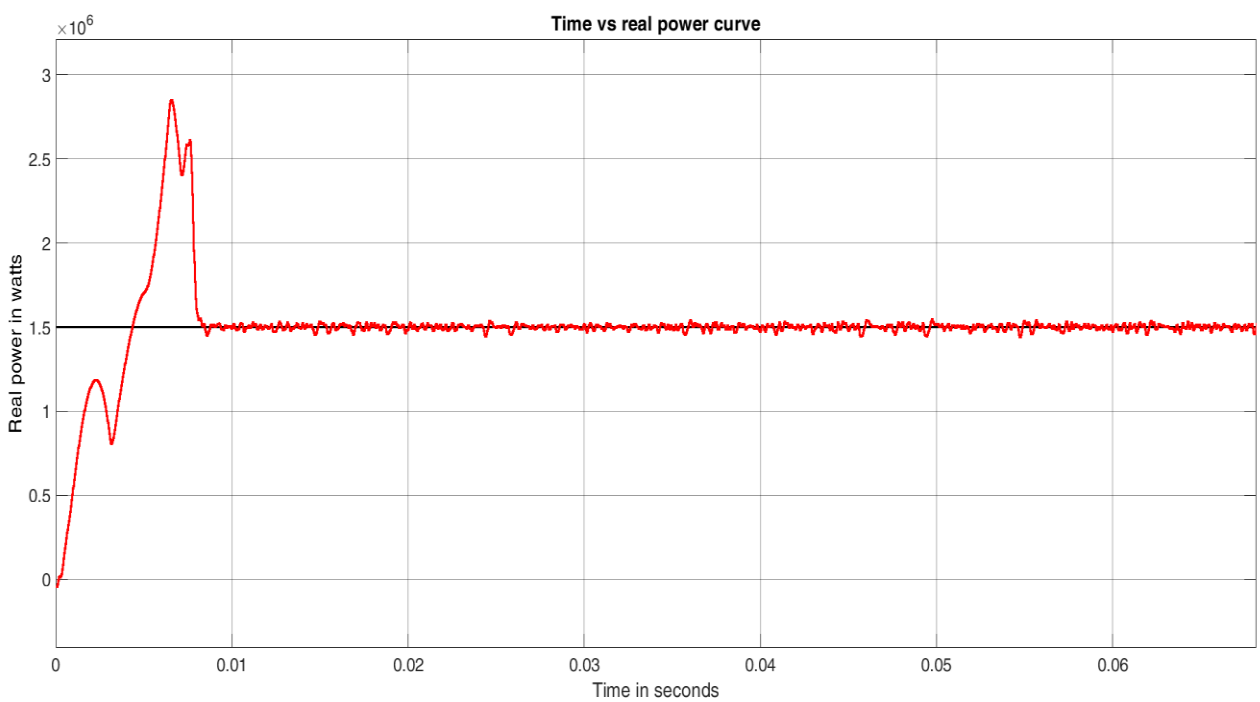


Figure 99: Time vs real power with controller

3. Inertia control

The wind turbine while running has a certain kinetic energy. When there is an instant demand of more power from the turbine then the inertial energy of the generator is extracted from the rotational masses.

The Simulink model of the grid side system has three controlling mode mentioned in *2.3.3 Outer loop design*. They are:

1) DC link voltage and reactive power, Q control mode,

2) id, iq control mode,

3) Real power, P and reactive power, Q control mode.

The detail explanation of each system has been discussed in that section. For a particular simulation purpose the selection mode is chosen from the Simulink model as shown in Figure 99. Normally, when the wind power is generating then the second mode is selected. In this mode the virtual inertia system triggers when it is required to inject extra inertial power to the grid.

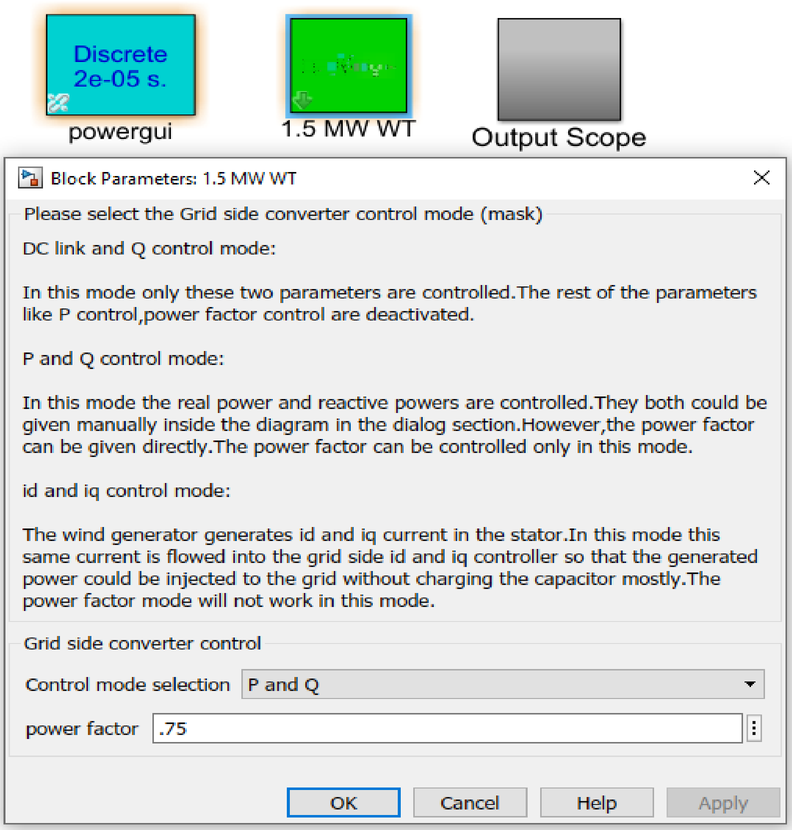


Figure 100: GSC selection mode.

In this section first of all the grid disturbance will be described, then the droop control of the PMSG will be discussed after that the inertial response and control of the wind generator will be explained in details.

3.1 Disturbance detection

Disturbance, Px can be defined as the unbalance between the instantaneous power and the load program. The unbalance condition generally comes from the integration or removal of generators or loads. [7]

In power system there is a relation between the real power and the frequency. The integration of the load in the system without control reduces the system frequency and vice versa. The characteristics has been shown in *Figure 101* below.

f_0=Nominal frequency
P_{L0}=Nominal power of the generator.
P_X=Disturbance in the system
LKL=load characteristics curve
Δf=change of frequency
ΔP=change of power
K_L= slope of load curve

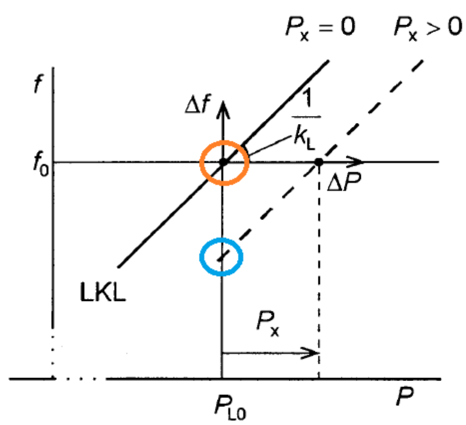


Figure 101:change of frequency with load [7]

In the figure above, at rated condition the load curve intersects the frequency at rated frequency (marked as red).It is assumed that there is no control on the generation side. Now, the disturbance (load) has been increased to Px .Due to this increased load it shifts the curve right side (marked as dotted line).This dotted line now intersecting the generator curve at a lower frequency (marked as blue).Hence, the system frequency has been decreased Δf amount.

Simulink block to detect the disturbance:

In the previous section it has been shown that the frequency changes with respect to the disturbance. So, the frequency is taken as a reference value to find a grid disturbance. The Simulink model has been designed to detect the frequency change so as the disturbance. First of all the speed has been measured whether it is above 0.5 rps or not. This is defined as condition 1.Since if the speed is below of this value then it has been considered that the system is not capable to deliver the inertial power. However, if

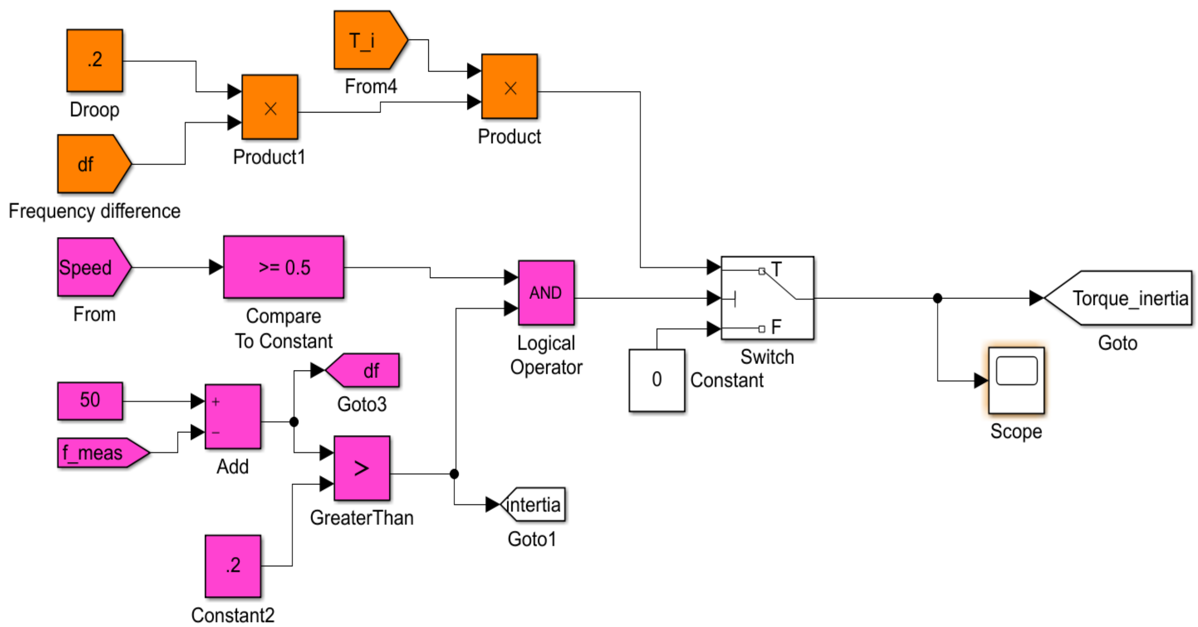


Figure 102: Simulink block diagram of disturbance detection

this condition satisfies then the grid input frequency has been checked and the difference has been measured (shown as pink color).If the difference is measured above a set value(for this case 0.2Hz) then this generates a true condition that the system is capable to deliver inertial power to the grid. This is defined as condition 2.If both the conditions are true then it would trigger a signal to activate droop control system. This droop control system is marked in orange color in Figure 101. Normally, if the inertial triggered signal is false then there will be no droop controlled power.

In the next section droop control system will be explained in details.

3.2 Droop control system

Droop control is a control strategy where the power output of the generator increases with a reduced frequency and decreases with a higher frequency of the grid. [33]

Droop curve formation:

The maximum power that can be injected from the rotor is 20% of the instantaneous power of the rotor. It has been taken as a reference that the rotor would deliver 20% more power when there is a disturbance in the grid. Another thing also being assumed that the rotor would deliver the maximum inertial power from the system when the frequency deviation is the maximum. For now, it has been taken that when the grid frequency falls below 50Hz and reaches to 49.5Hz, the system would deliver this power. Conversely, if the frequency goes above 50Hz and reaches at 50.5Hz, then we would reduce the production by 20% just like before. In practical case the grid does not go above 50.5 Hz and below 49.5Hz.So, the system has been limited within this frequency range.

For a frequency deviation(Δf),the slope of the network characteristic curve(K_N) and the disturbance of the network is P_X .The relationship between these three parameters can expressed by the following equation [7]:

$$\Delta\mathrm{f} = -\frac{P_X}{K_N}$$

The frequency vs power curve has been summarized below:

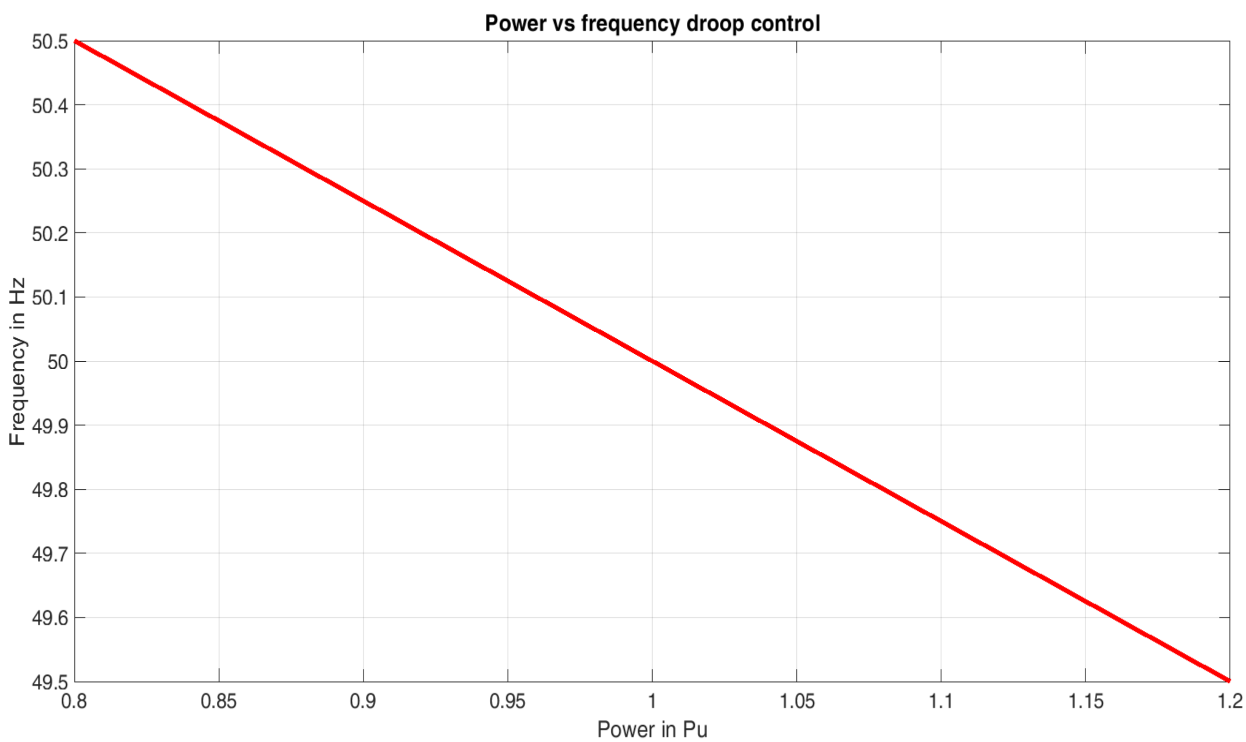


Figure 103: Frequency vs power curve

3.3 Inertial response

When the output of the pink marked section in Figure 103 is true then it triggers a signal which activates the droop control system. After that this output is added with the generator main torque marked as Torque_intertia block in Figure 104. When the inertial response triggers then the MPPT controller shown in Figure 104 is turned off. The torque output of this moment is kept constant at the present value. The memory block is placed there to take the immediate value before inertial response. This memory block stores the torque value constant until the control signal becomes zero. The torque value does not change at the time of inertial response.

When the triggering signal is zero then the system falls back to the MPPT controlled system again.

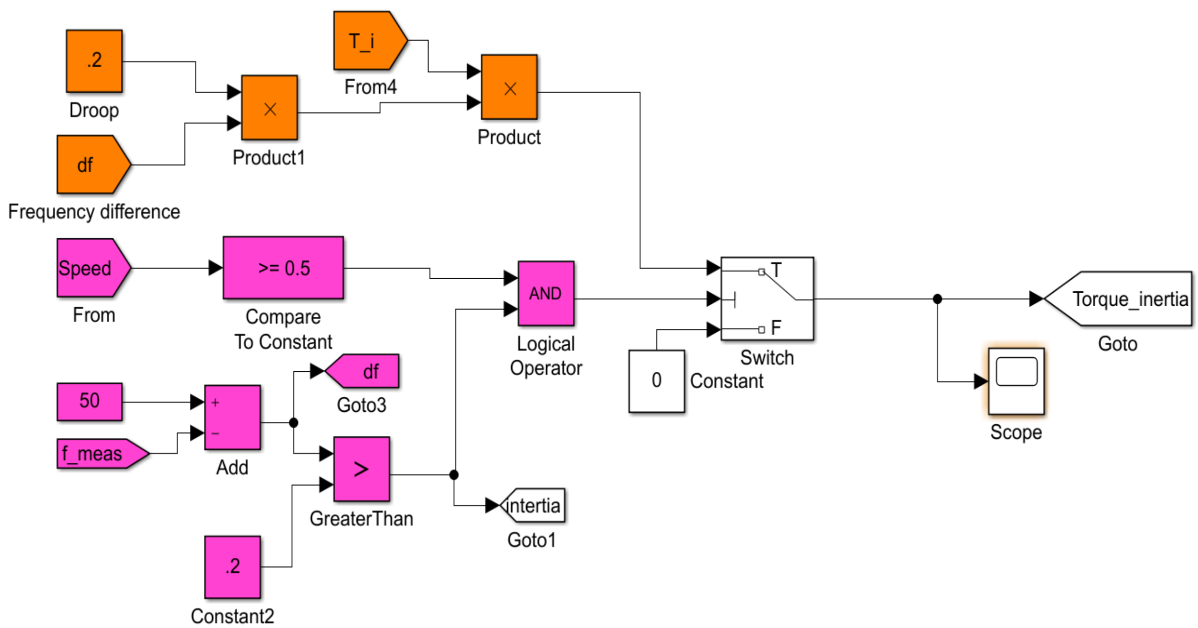


Figure 104: Droop control output block

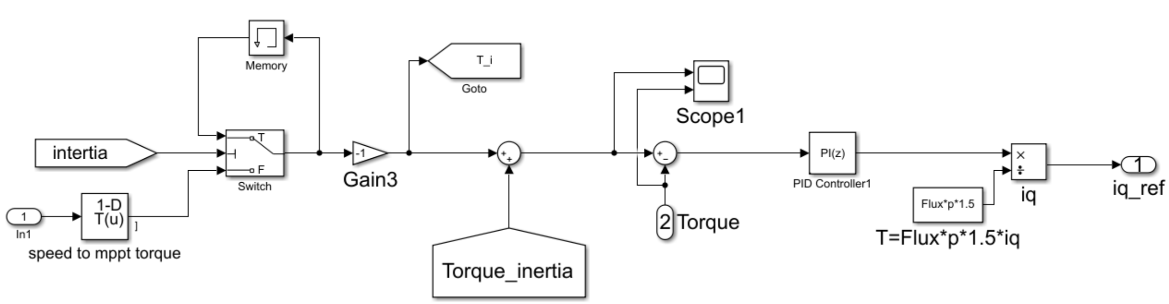


Figure 105: Inertia simulation block

Simulation:

In order to simulate the inertial response behavior there is frequency drop in the grid from 33s to 63s has been created. The corresponding torque, power change are shown in Figure 105& Figure 106 respectively.

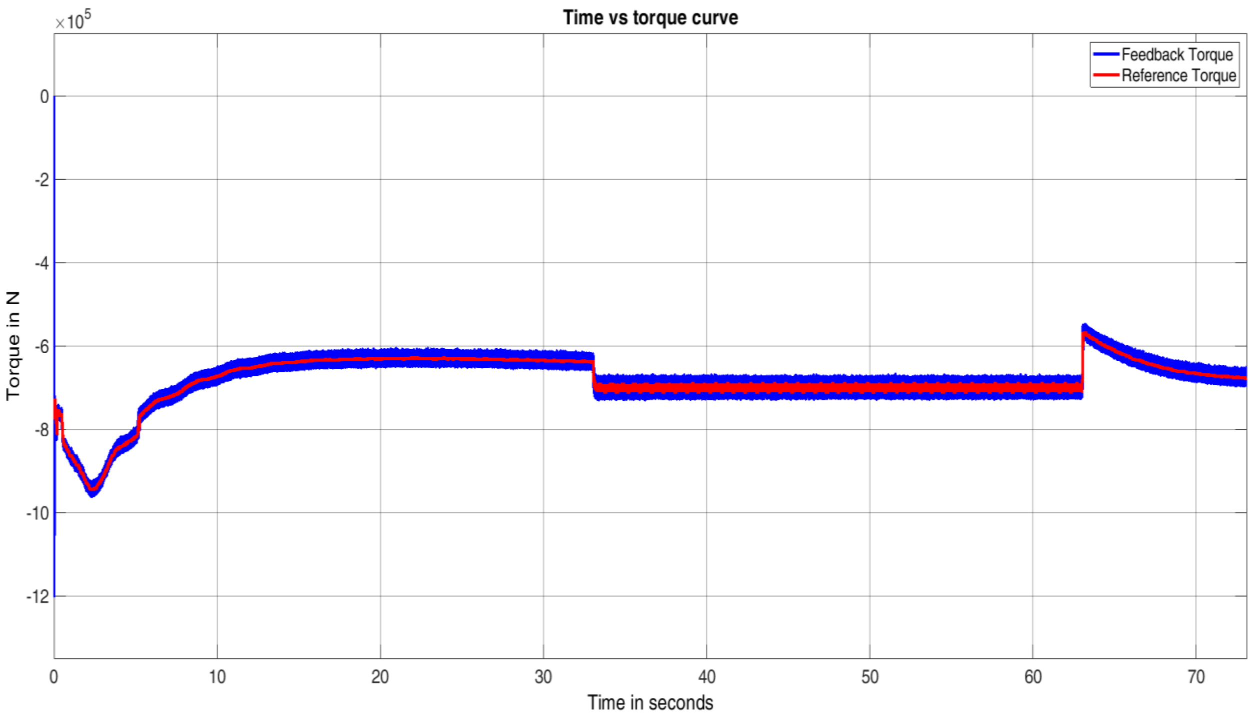


Figure 106: Time vs torque inertial response

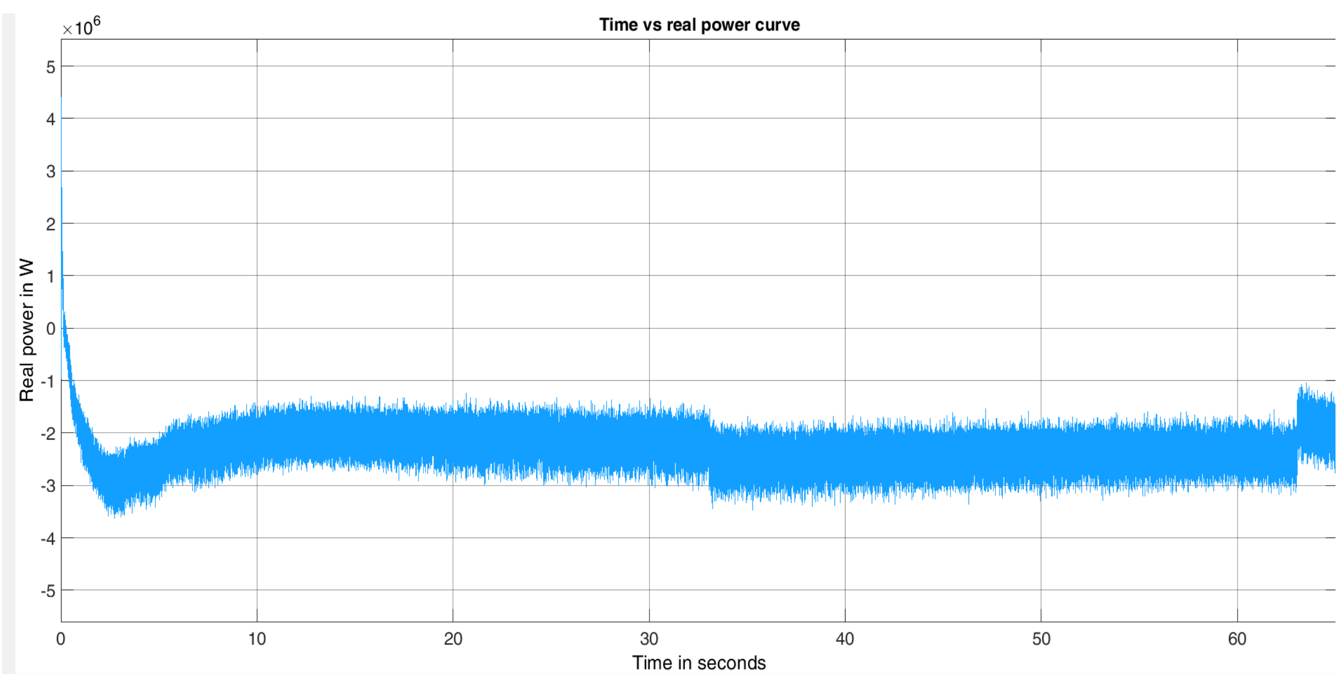


Figure 107: Time vs real power curve

It is seen that at 33rd second the inertial control system triggered and the torque instantly takes the fixed value with the control system logic. Because of the droop controller mounted on the inertia controller the torque increases about 20% from it's instantaneous value. So as the power also increased. The speed curve is shown in Figure 107 below. In the speed curve it is seen that when the inertia controlled system triggered at 33rd second then the kinetic energy of the rotor has been transmitted to the output and the speed gradually decreases till 63rd seconds. After that when the inertial control is over then the speed started boosting up again.

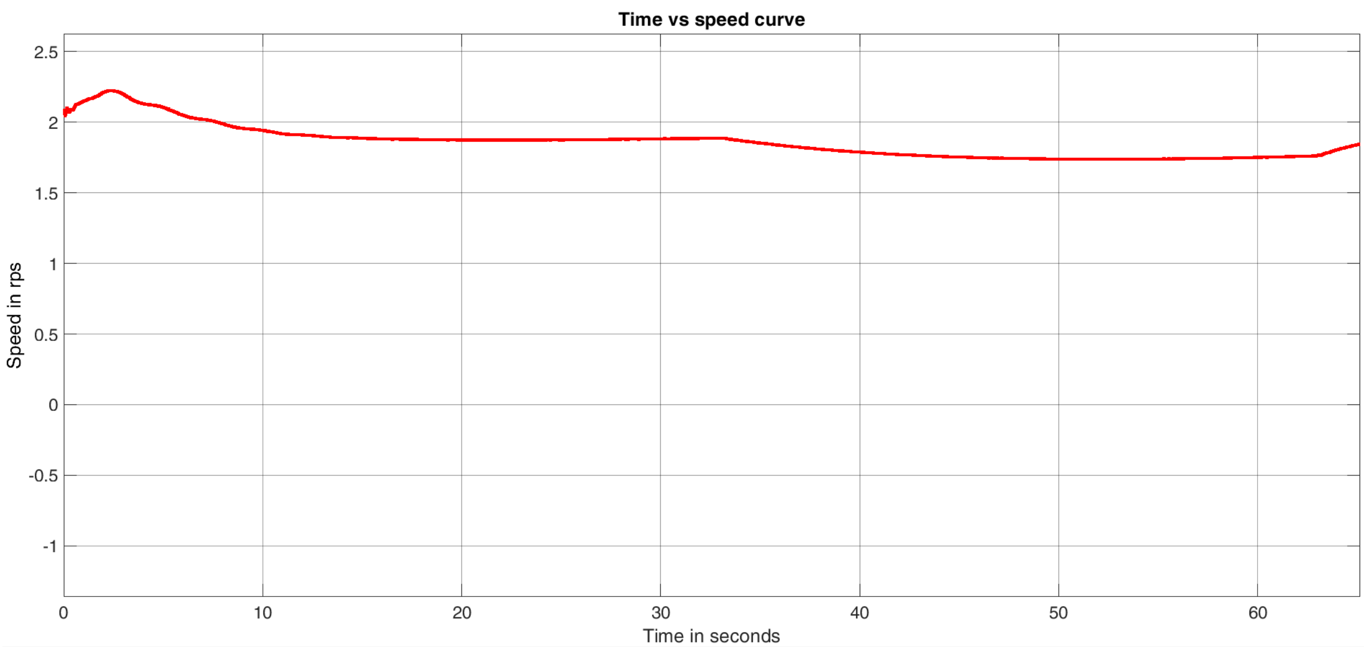


Figure 108: Time vs speed curve

4 Simulation result with a time varying Wind speed

In this section a time varying wind speed will be applied to the wind turbine and the corresponding current, voltage, torque will be observed. Additionally, a frequency drop will be created to see the inertial performance with a time varying wind speed.

The time varying wind speed range that has been applied to the wind turbine is shown in the Table 16 below.

In Figure 108 the grid side and machine side current voltages have been shown. In Figure 108a the machine side id current is set to zero since the reactive power is made to zero. It is expected that only the real power is generated in the stator of the machine. In 64b the iq axis current of the machine side has been shown. There is a frequency drop created between 33s and 43s.The generator tends to generate more power from the kinetic energy of the rotor which is completely reflected in Figure 108b.

Table 16: Time vs wind speed

Time	Wind speed
0	10
21.9	8
26	10.5
31.9	15
33	10.5
43	10.5
45.9	10
48	13
50.9	15
53	12
55.9	8
54.9	23
56	17
59.9	10.3
61	20
65.9	15
69.9	18
75	12
80.9	8
84.9	23
85	17
89.9	10.3
91	20
95.9	10
100.9	18

In Figure 108c and Figure 108d the grid side voltage and currents have been shown. The terminal voltage tends to decrease while current increases between 33s and 43s.In Figure 108h it is seen that when there is a frequency drop in the system then the generator generates more power in this range of time. Figure 64g shows the voltage curve of the grid side. The terminal voltage remains the same while the line current increases in the frequency dropping period.

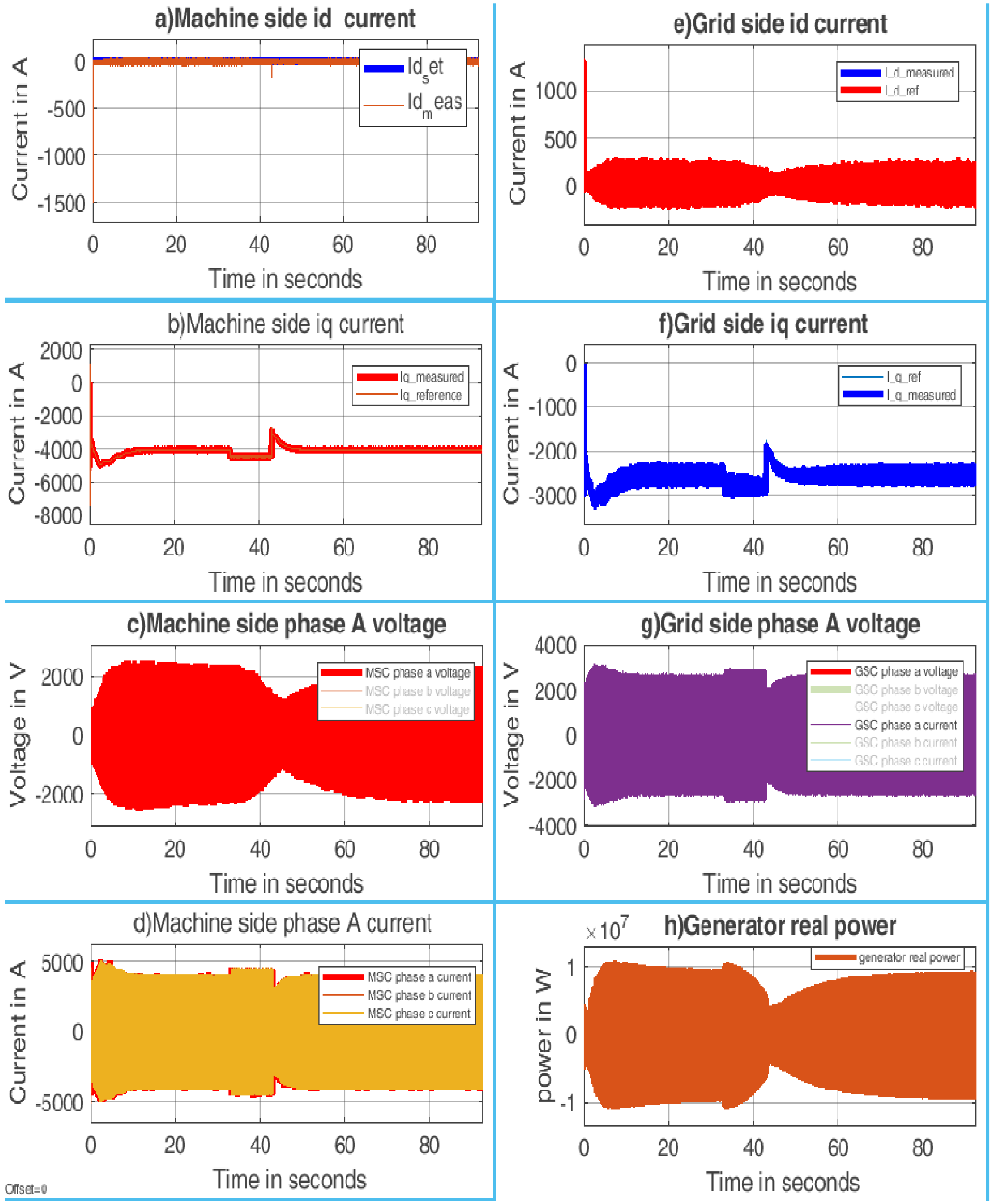


Figure 109: Output voltage, current of machine side and grid side with time varying wind speed

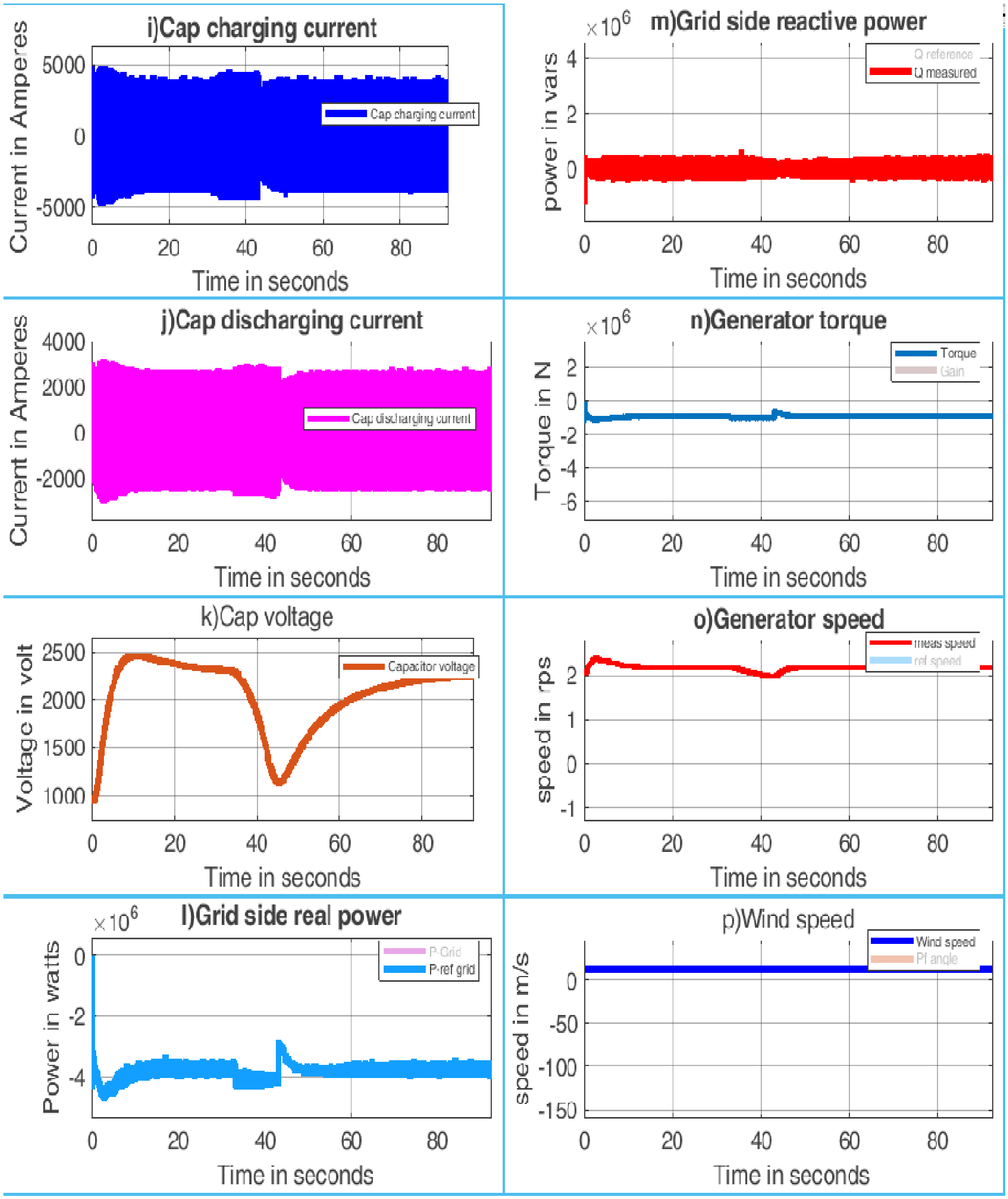


Figure 110: Capacitor voltage, current, generator power, torque, wind speed with time varying wind speed

In figure 65I the capacitor charging current has been shown. When the virtual inertia control triggered then there is a slight increase of charging current in the capacitor between 33 and 44 seconds. Figure 109j the capacitor discharging current has been shown. This current is flowing from the dc link capacitor to the grid side. This current has both positive part and negative part, it means that there is a reactive power flowing in the system.

Figure 65K shows the status of the dc link capacitor voltage. The dc link capacitor charges before the frequency drop period since only 60 percent of generator side current was flowed in the grid side converter and the rest of the current was used to charge the capacitor. At 33s when the virtual inertia period triggered then the capacitor begin to discharge since the droop controller takes the power from the generator rotating masses and the dc link capacitor as well. After the virtual inertia control period the voltage begins to rise again.

The grid side real power status has been shown in Figure 109l. In this figure it is seen that between 33s and 44s the real power increases 20 percent and after that it decreased again. The reactive power of the grid side has been shown in Figure 109m.It is kept always at zero since it is not expected to flow a reactive power to the grid.

The generator torque and speed curve have been shown in Figure 109n and Figure 109o respectively. In torque curve the torque increases at 33s and remains stationary till 43s because of virtual inertia control and after that it decreases again. The speed starts to decrease at 33s and continues to decrease till 43s because the rotational energy of the rotor has been transferred to the grid. After that when the virtual inertia control period is over it starts to increase again.

The status of the wind curve has been shown in Figure 109p.Particularly, the wind velocity with respect to time has been shown in Table 16.It is seen in Figure 109I that the generated power in the generator changes with respect to the wind speed.

5. Conclusion

In this master thesis, a real world problem has been addressed analytically. First section was dedicated for the wind power generation and dc link capacitor charging issue. The second was more complex than the first part since it is very much difficult to be synchronized with the grid. In the last section a unique torque controller has been designed and the desired virtual inertia control mechanism has been implemented .The results found in the end fulfills the goal of this thesis.

However, there are some other integral tasks which could be analyzed in future. Everywhere in the model the PI controllers have been used. There might be PR controllers or Fuzzy logic controllers used to see better performances. The usage of DFIG in place of PMSG could be analyzed. For MSC and GSC, 3 level converters have been used. But higher level of MMC could reduce the size of the filters and hence the overall cost also.

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