FOC FOR PMSM REPORT

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1. Abstract

This report explores Field-Oriented Control (FOC) for Permanent Magnet Synchronous Motors (PMSMs). It covers key elements like tuning current control, creating a mathematical model for PMSM, using Space Vector Modulation (SVM), and showing some results to test the tuning of current control.

2. FOC implementation

Steps

1. Coordinate Transformation

Transform the motor's three-phase currents from the stationary reference frame (abc) to a rotating reference frame (dq-axis) aligned with the rotor. This involves using math to change the way we look at the currents, making it easier to control the motor.

2. Control of Currents

Separate the transformed currents into two parts: the direct-axis current (Id) and the quadrature-axis current (Iq). Use simple controllers, like PI controllers, to manage these currents. Control Id to control the flux and Iq to control the motor's torque.

3. Flux Weakening (if needed)

To make the motor go faster than usual, adjust the flux by reducing Id. This lets the motor handle higher speeds, but the torque will reduce.

4. Inverse Transformation

Convert the controlled currents from the dq-axis reference frame back to the abc reference frame. This step is like undoing the first transformation so that the motor can understand the control signals.

5. Voltage Inverter

Use an inverter to send the right voltage to the motor's stator windings.

6. Feedback and Iteration

Continuously measure the motor's currents and rotor position to see if they match the desired values. Adjust the control signals based on the measurements to correct any errors and keep the motor running smoothly.

Mathematical Modelling of PMSM

Equations:

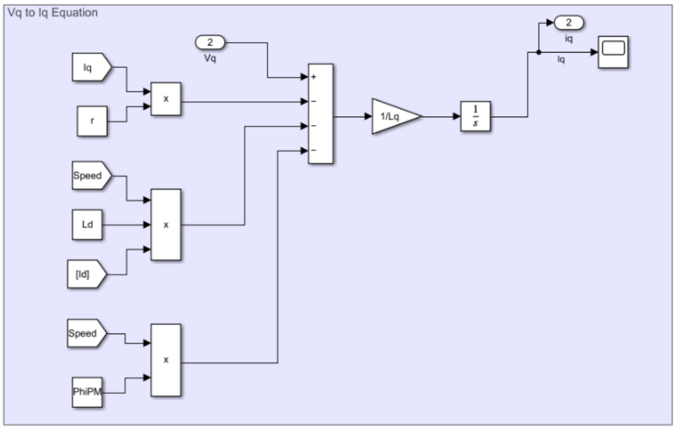
$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q$$

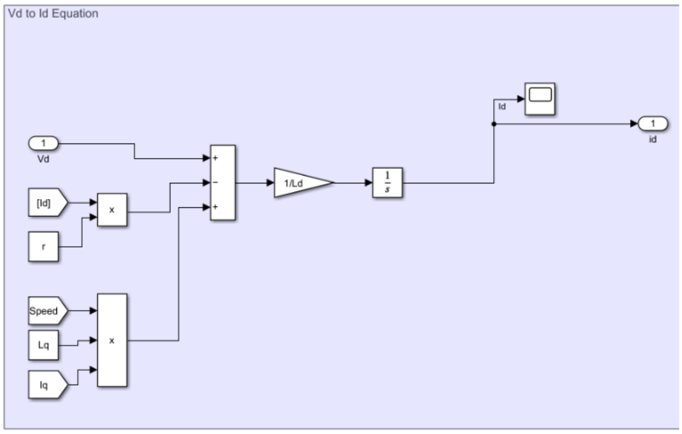
$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \psi_{PM}$$

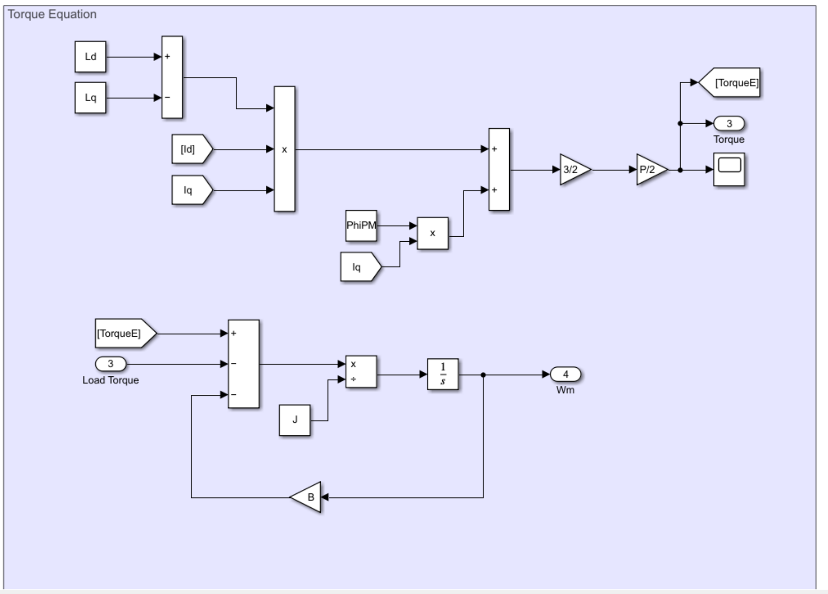
$$T_{dev} = \frac{3}{2} P((L_d - L_q) i_d i_q + \psi_{PM} i_q)$$

$$\theta = \int \omega \, dt$$

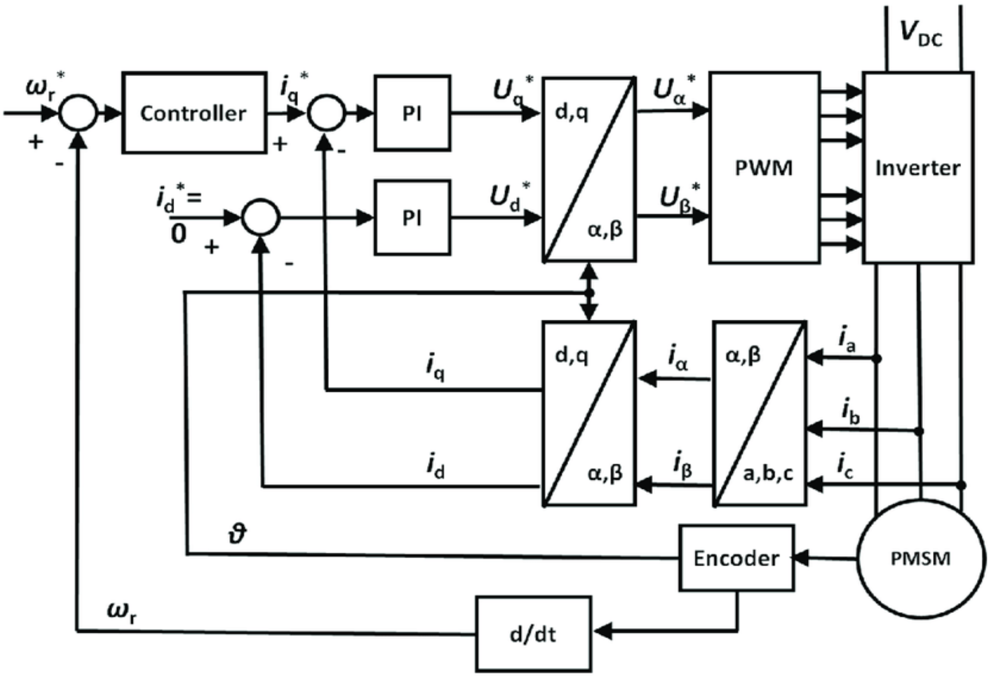
$$I_{stator} = \sqrt{I_d^2 + I_q^2}$$







FOC for PMSM



Block diagram FOC for PMSM

Current loop

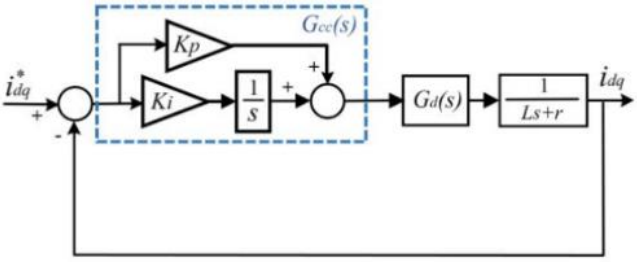
The PI controller is commonly used in vector control and used to regulate the Id and Iq currents. The PI controller takes the error between the desired current and the actual current as input and produces a control signal to adjust the voltage applied to the motor.
The proportional term in the PI controller responds to the current error, and the integral term responds to the accumulated error over time.

The use of PI controllers in the FOC system ensures that the motor current is accurately regulated, which is essential for achieving high-performance control of the motor. The PI controller adjusts the voltage applied to the motor to maintain the desired current level, which in turn controls the motor torque and flux (Field Weakening).

Tunning methods:

1. Pole Zero Cancelation

$$G_{O\cdot L}(s) = \frac{k_o}{s} G_d(s)$$



$$G_{C\cdot L}(s) = \frac{k_o G_d(s)}{s + k_o G_d(s)}$$

$$G_d = \frac{1 - \frac{T_d}{2} S + \frac{T_d{}^2}{12} S^2}{1 + \frac{T_d}{2} S + \frac{T_d{}^2}{12} S^2}$$

$$T_d = 1 * T_{sampling}$$

$$T_{sampling} = \frac{1}{f_{sw}}$$

Choose $k_o = 0.33\, f_{sw}$ to achieve the strongest disturbance rejection

$$k_i = k_o r$$

$$k_p = k_o L$$

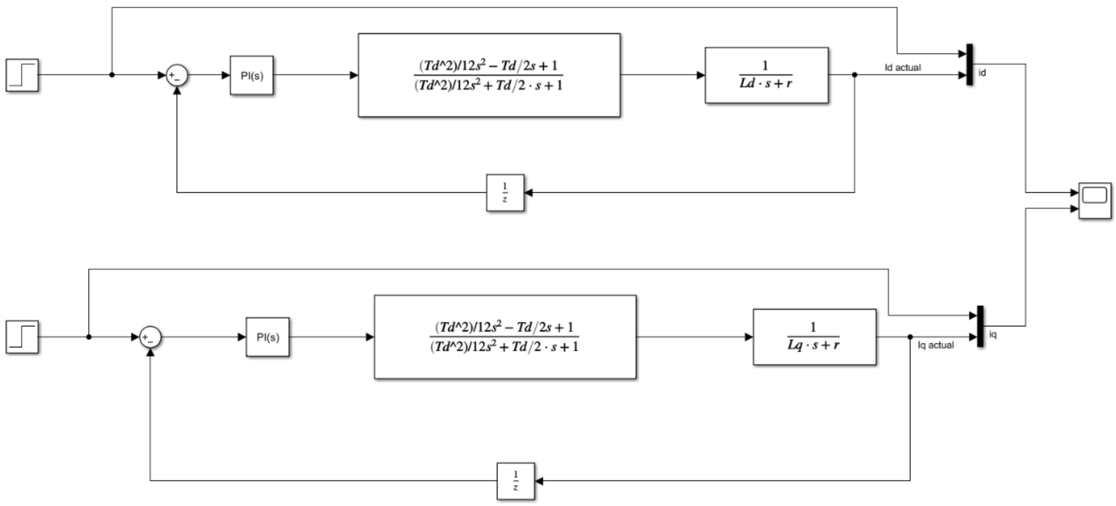
r and L from machine parameters

r=1.2Ω, L_q= 0.0125H, L_d = 0.0057H, f_{sw} = 5000

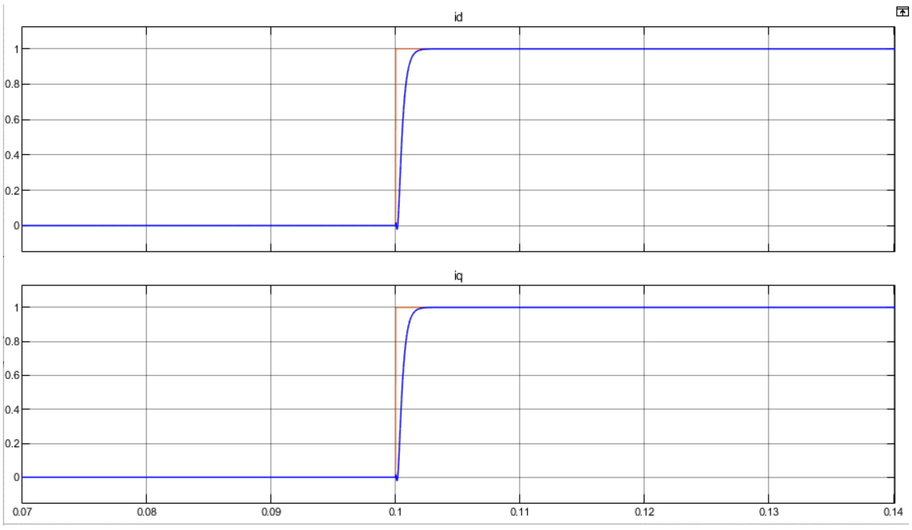
$$k_i = 1980$$

$$k_{p\ for\ Id} = 9.405$$

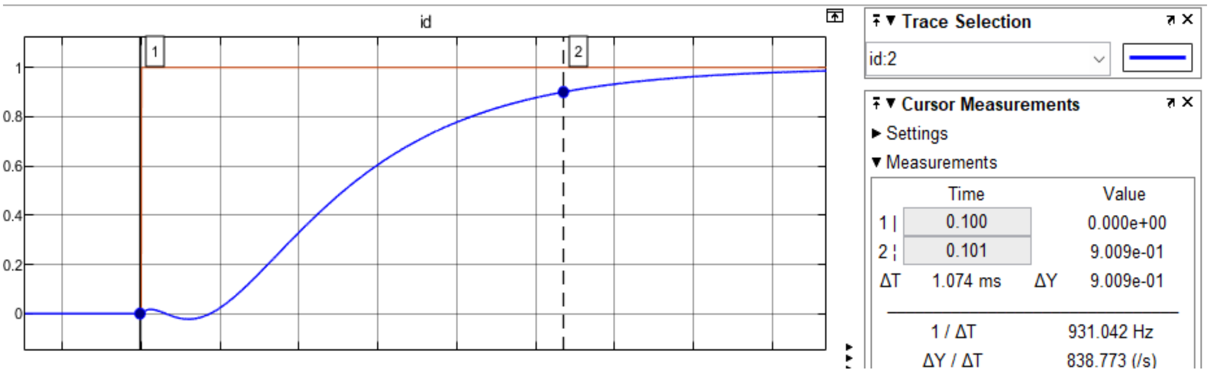
$$k_{p\ for\ Iq} = 20.625$$



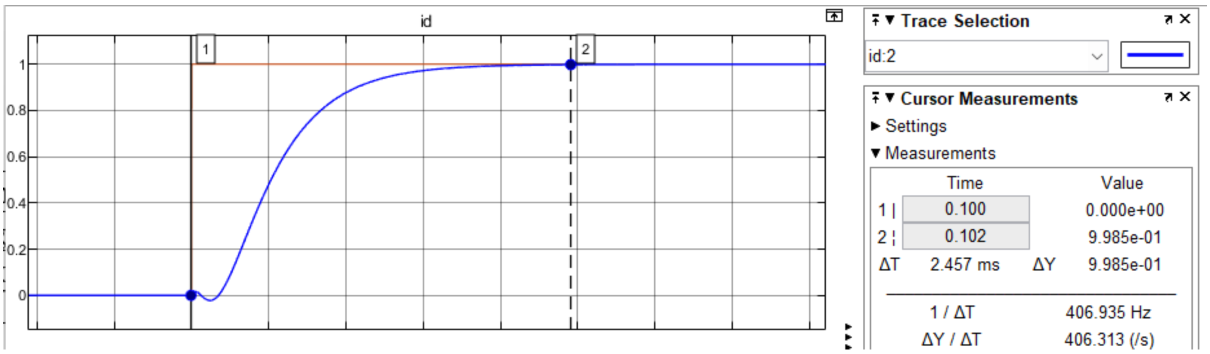
Pole zero cancelation tunning method



Current loop using step input 1st method.



rise time (90% of setpoint)

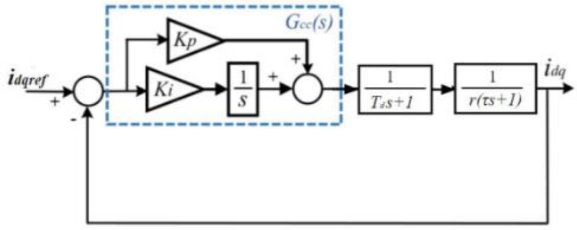


settling time

rise time	1.074 ms
settling time	2.547 ms
overshoot	0%

2. Modulus Optimum

$$G_{O \cdot L}(s) = k_p \frac{1 + T_i s}{T_i s} * \frac{1}{1 + T_d s} * \frac{1}{r(\tau s + 1)}$$



$$G_{C \cdot L}(s) = \frac{\frac{K_v}{T_d}}{S^2 + \frac{1}{T_d} s + \frac{K_v}{T_d}}$$

$$K_v = \frac{K_p}{r\, T_i}$$

$$\tau = \frac{L}{r}$$

$$T_i = \tau$$

$$K_p = \frac{r\, T_i}{2\, T_d}$$

$$K_i = \frac{K_p}{\tau}$$

$$T_d = 1 * T_{sampling}$$

Using machine parameters

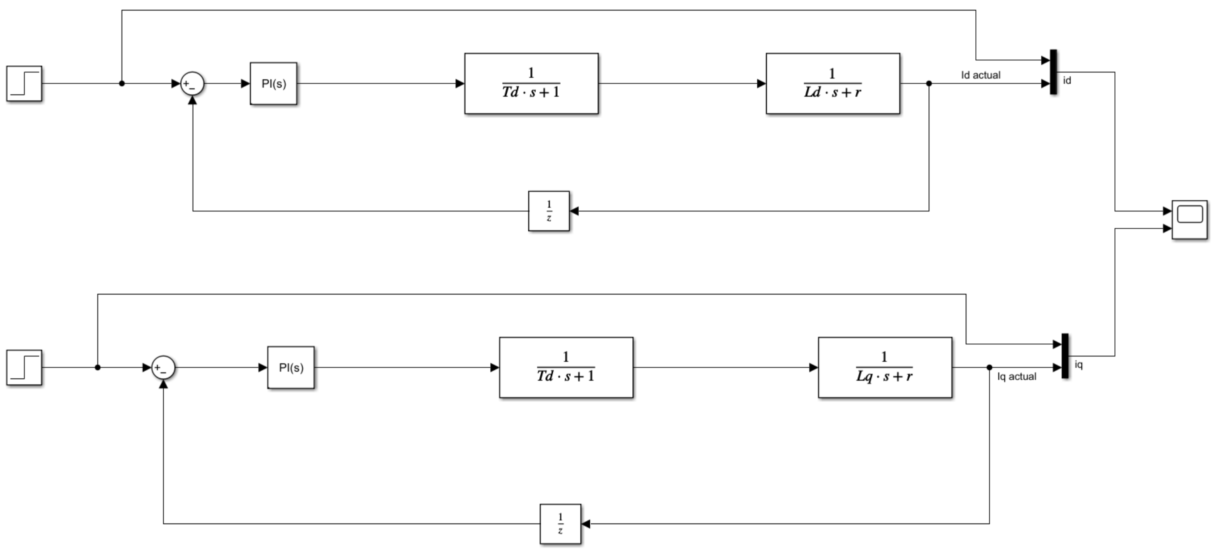
r=1.2Ω, L_q= 0.0125H, L_d = 0.0057H, $T_{sampling} = \frac{1}{f_{sw}}$

$$k_{i\ for\ Id} = 3000$$

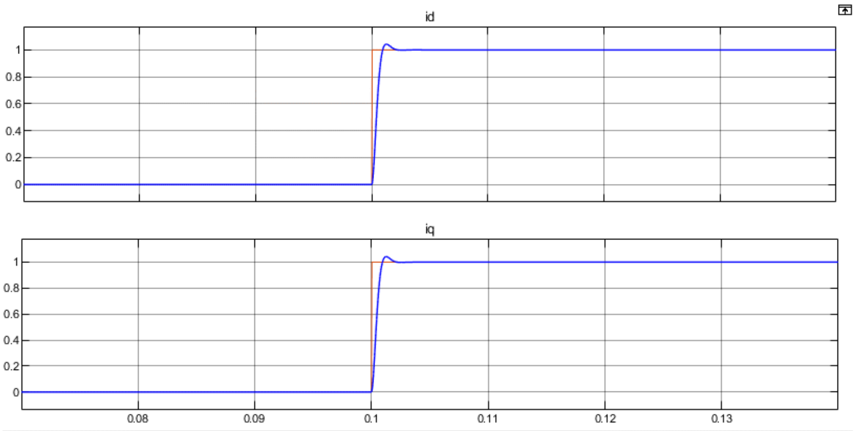
$$k_{p\ for\ Id} = 14.25$$

$$k_{i\ for\ Iq} = 3000$$

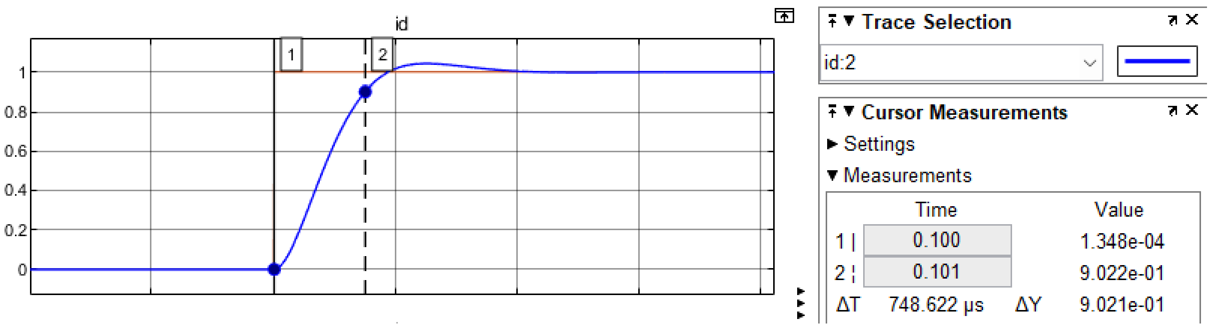
$$k_{p\ for\ Iq} = 31.25$$



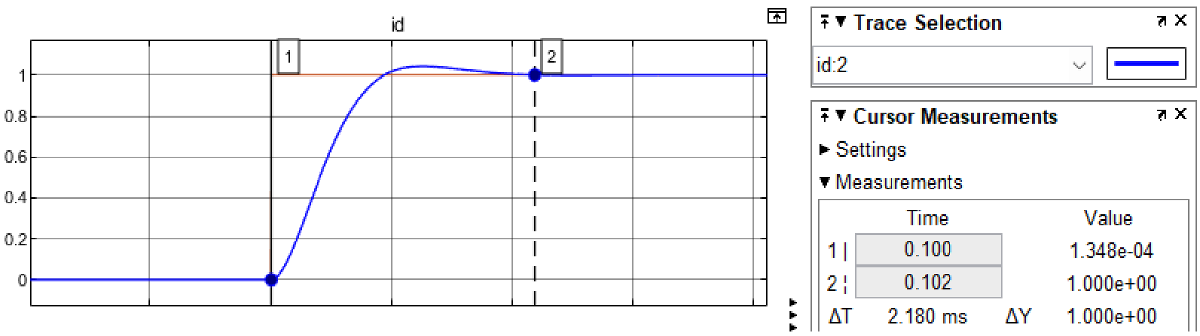
Modulus Optimum tunning method



Current loop using step input 2nd method.



rise time (90% of setpoint)

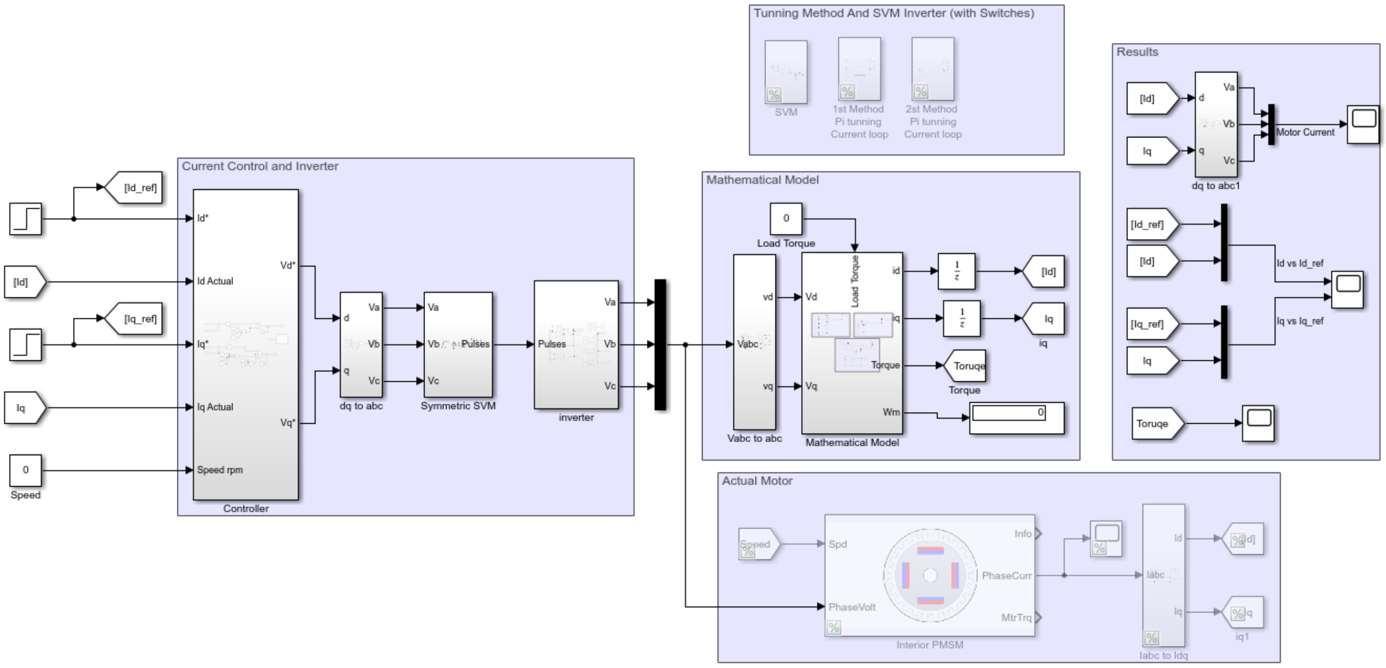


settling time

rise time	0.748622 ms
settling time	2.18 ms
overshoot	4.33%

<u>Utilizing the anti-windup clamping technique with a threshold of Vdc/sqrt(3).</u>

3. MATLAB Model



MATLAB Model

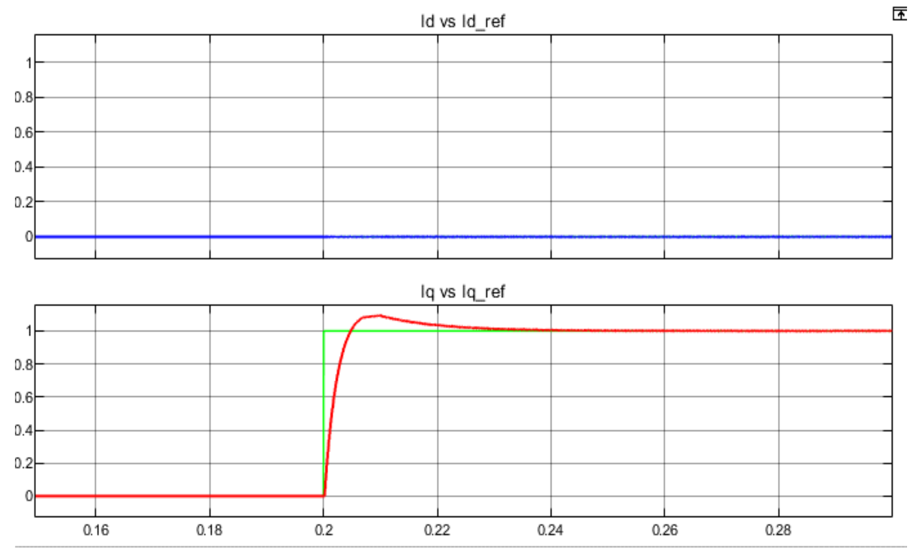
First, we start by providing reference values for Iq and Id currents, as well as the desired speed, to the controller block. This controller block then produces Vqref and Vdref values. These values are then transformed using Clarke and Park transformations to obtain Vabcref, which represents the three-phase voltage references.

Next, these Vabcref values are input into the symmetric Space Vector Modulation (SVM) block. This block generates the necessary pulse patterns that are sent to the inverter block. The inverter block uses these pulse patterns to produce the corresponding three-phase voltages, which are then applied to the motor.

Inside the motor, these voltages undergo a transformation to Vdq values. These Vdq values are then used in the mathematical model of the Permanent Magnet Synchronous Motor, which accurately describes the behavior of the PMSM or used in the actual Motor. We select one of them and comment the other. As a result of this modeling, we obtain outputs for Iq and Id currents, torque, and motor speed.

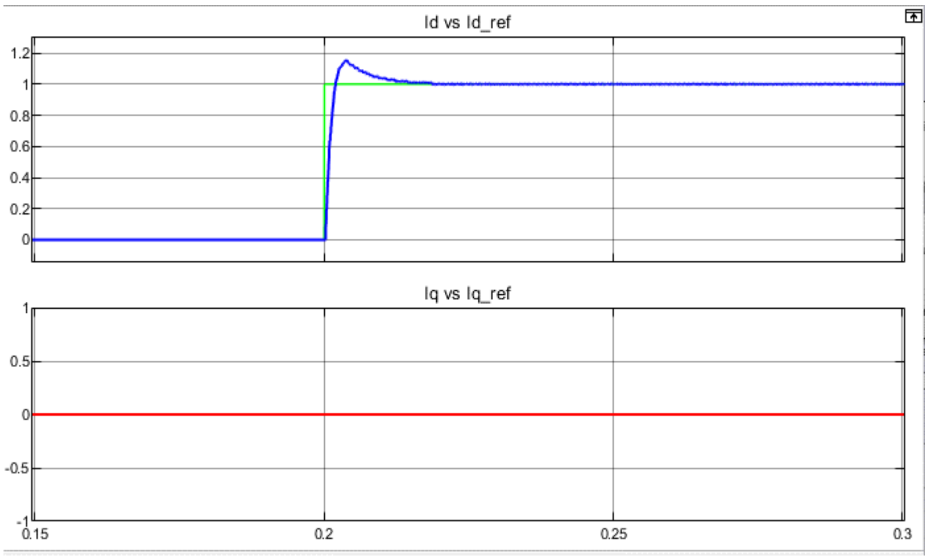
Simulation results

- **Speed=0, Id=0, Iq step response to 1A**



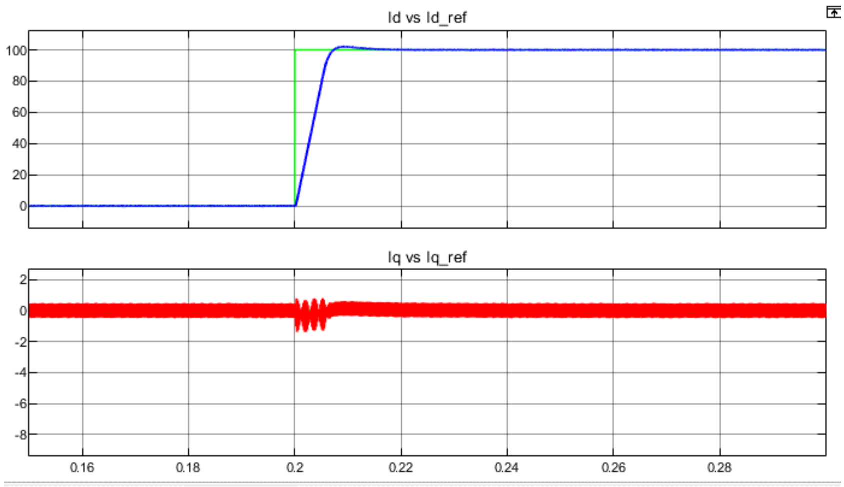
Input step response for Iq at t=0.2s

- **Speed=0, Iq=0, Id step response to 1A**



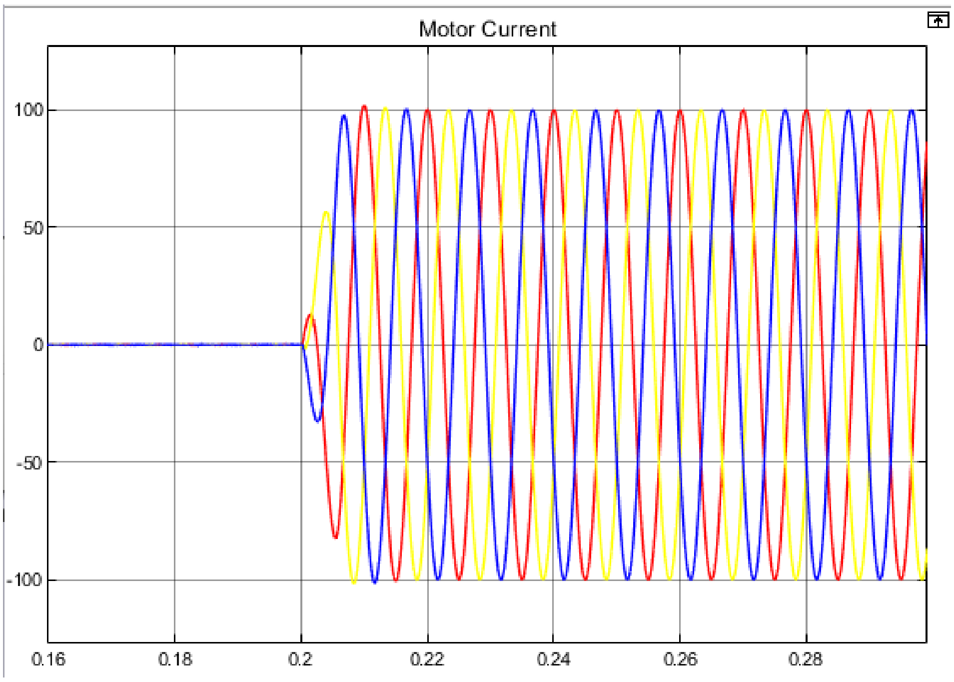
Input step response for Id at t=0.2s

- **Speed=3000 rpm, Iq=0, Id step response to 100A (without decoupling)**

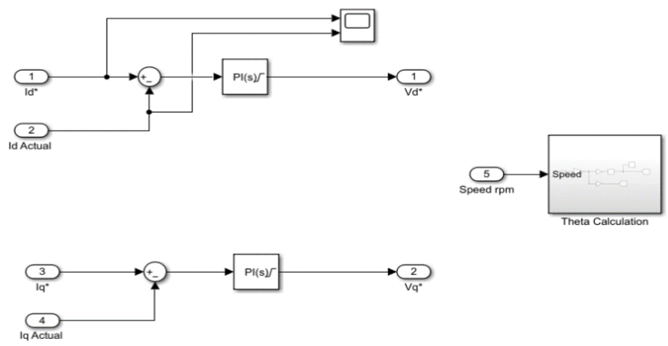


Input step response for Id at t=0.2s without decoupling

➢ **Motor current**

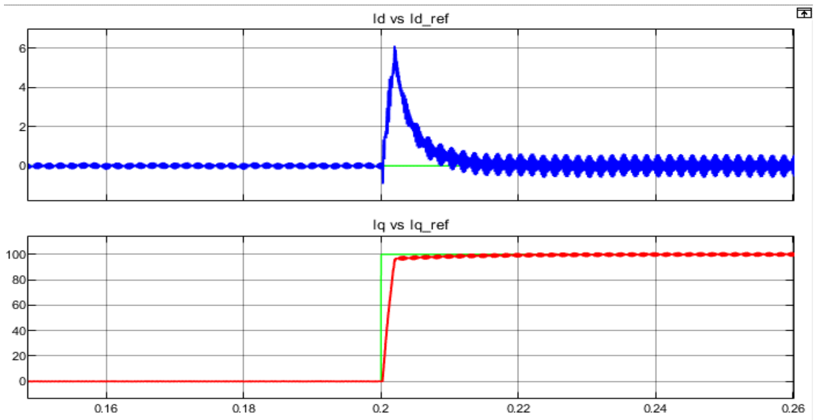


Motor current



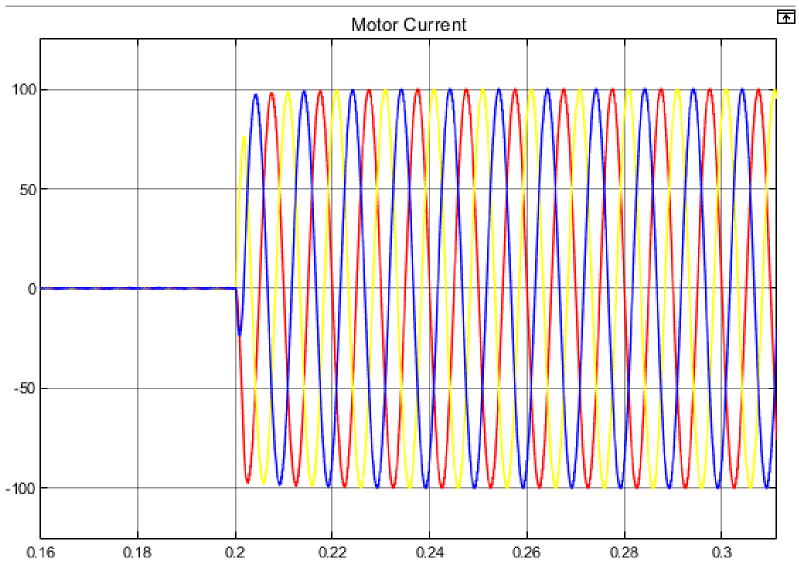
Without decoupling

- **Speed=3000 rpm, Id=0, Iq step response to 100A (with decoupling)**

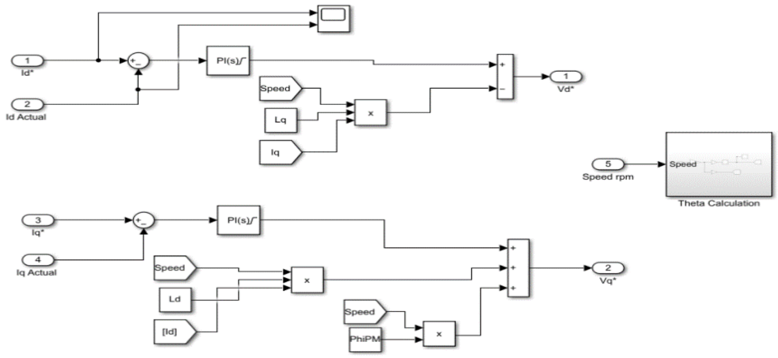


Input step response for Id at t=0.2s with decoupling

➢ **Motor current**



Motor current

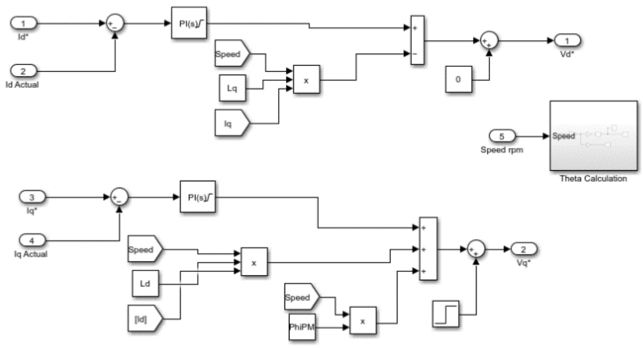


With decoupling

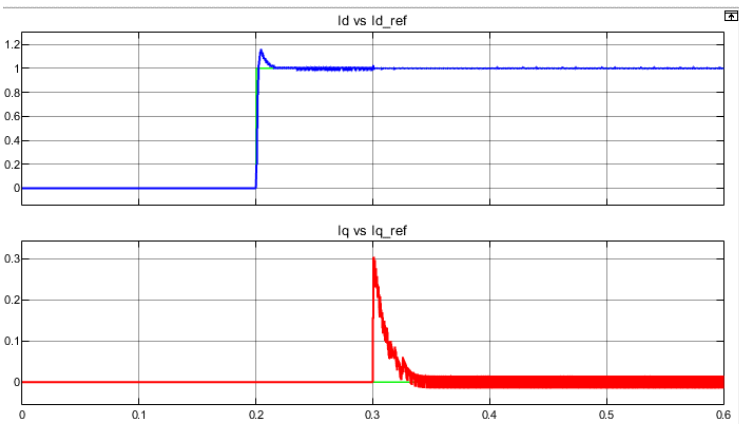
Comment:

The difference between using decoupling or not is how the system handles changes, for example in the Id value. When we adjust Iq, it doesn't have a big effect on Id thanks to the decoupling. The PI controller in the dq domain helps bring back the Id value to what it was before we changed Iq.

- Apply a step disturbance of 10 V to the Vq

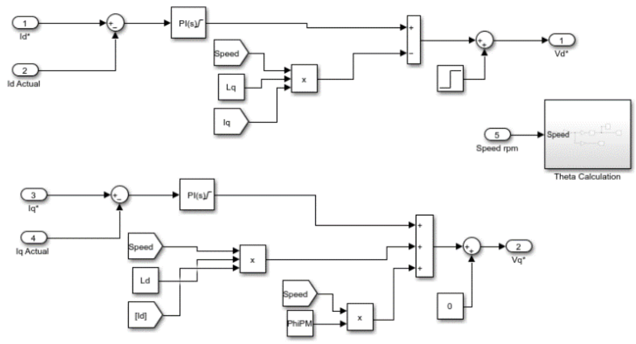


Applying a step disturbance for Vq

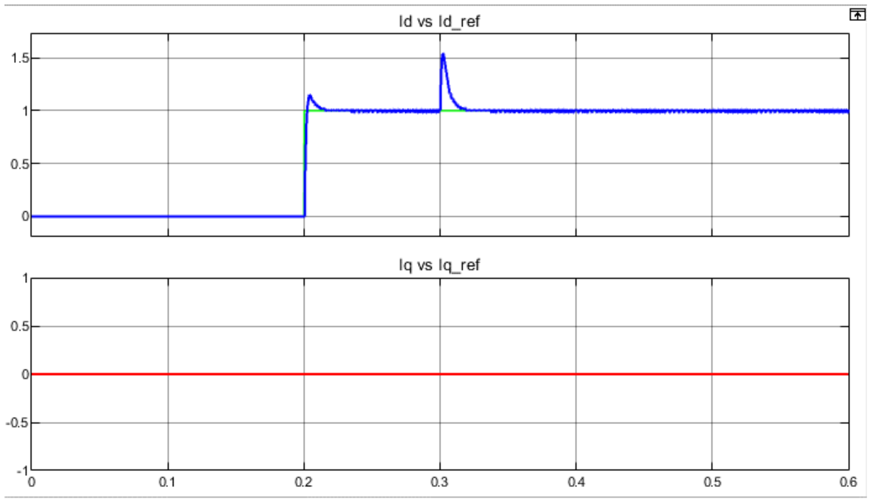


step response disturbance for Vq at t=0.3s

- Apply a step disturbance of 10 V to the Vd



Applying a step disturbance for Vd



step response disturbance for Vd at t=0.3s

Parameter	Value	Parameter	Value
Stator resistance per phase	1.2 Ω	Base power loss	121 W
Q axis inductance	0.0125 H	Base torque	2.43
D axis inductance	0.0057 H	Base current	4.65 A
Rotor flux linkage	0.0123 Wb	Number of poles	4
Inertia	$0.0027\ \mathrm{kg.\,m^2}$	Vdc	700 V

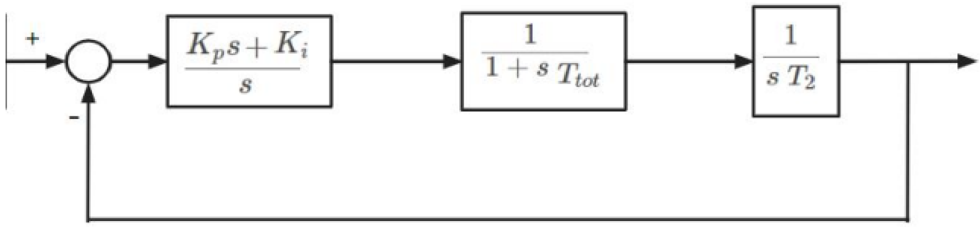
Speed loop

$$G = \frac{1}{JS + B}$$

If the effect of friction is neglected and only inertia is considered, then the resulting analysis or model would be simplified and focused solely on the system's kinetic properties and behavior.

$$G = \frac{1}{JS} = \frac{1}{T_2 S}$$

According to the transfer function, the plant is a 1st order system. Therefore, a PI controller is sufficient to follow a constant reference with no permanent error. The proportional and integral terms are tuned using the Symmetrical optimum criterion.



$$T_{sens} = 0$$

$$T_{ctrl} = N * T_{sw}$$

$$T_{PWM} = \frac{T_{sw}}{2}$$

$$T_{sw} = \frac{1}{F_{sw}}$$

The total delay of the outer loop is then the sum of the small-time constants:

$$T_{tot} = T_{sens} + T_{ctrl} + T_{PWM}$$

$$T_N = 4T_{tot}$$

$$T_i = 8 * \frac{(T_{tot})^2}{T_2}$$

$$K_P = \frac{T_N}{T_i}$$

$$K_i = \frac{1}{T_i}$$

	Symbol	**Definition**
Sensing delay	T_{sens}	Delay in the measured quantity, due to finite sensor and analog chain bandwidth, and possibly filtering delay
Control delay	T_{ctrl}	Delay between sampling instant and duty-cycle update instant in the PWM modulator
Modulator delay	T_{PWM}	Average delay between duty-cycle update in the PWM modulator and resulting change in modulator output
Total loop delay	T_{tot}	Sum of the above delays, representing the total delay of the control system
Switching Frequency	F_{sw}	The switching frequency of the inverter
	N	the ratio of the execution rates of the speed control and current control loops.

The speed controller is executed 10 times slower than the current control (N=10).

The equations presented in the preceding discussion can be used to calculate the values of the proportional gain (K_P) and integral gain (K_i).

$$T_{tot} = 2.1 * 10^{-3}$$

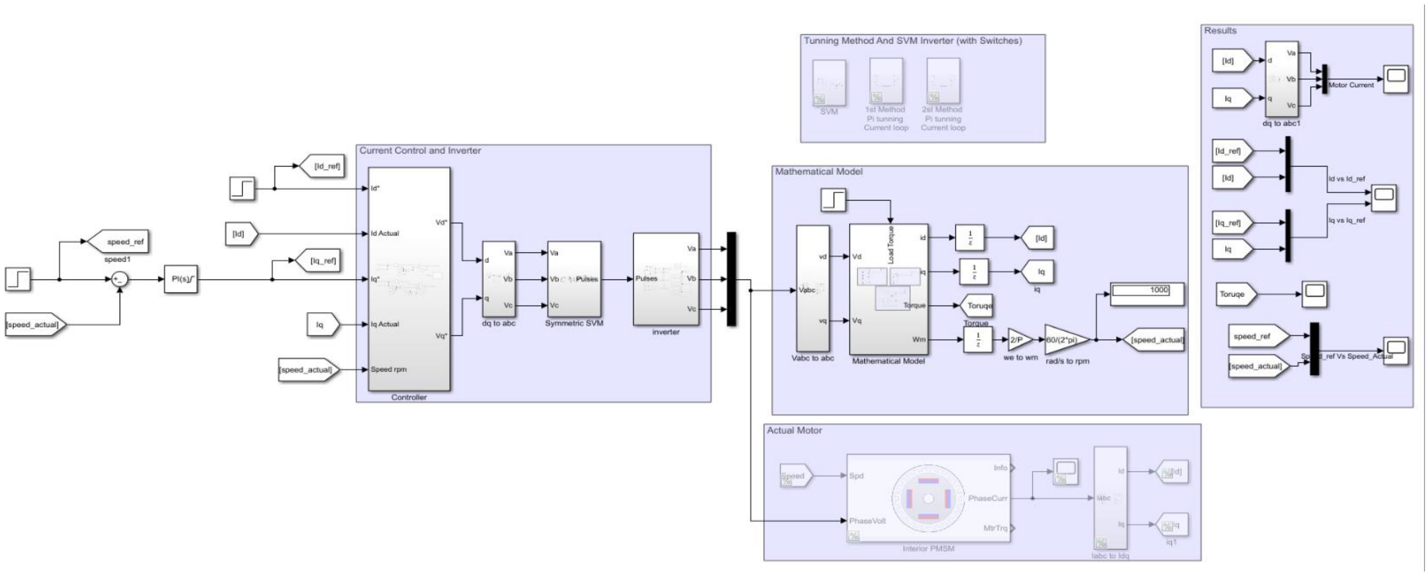
$$T_N = 8.4 * 10^{-3}$$

$$T_2 = J = 0.0027$$

$$T_i = 0.013066667$$

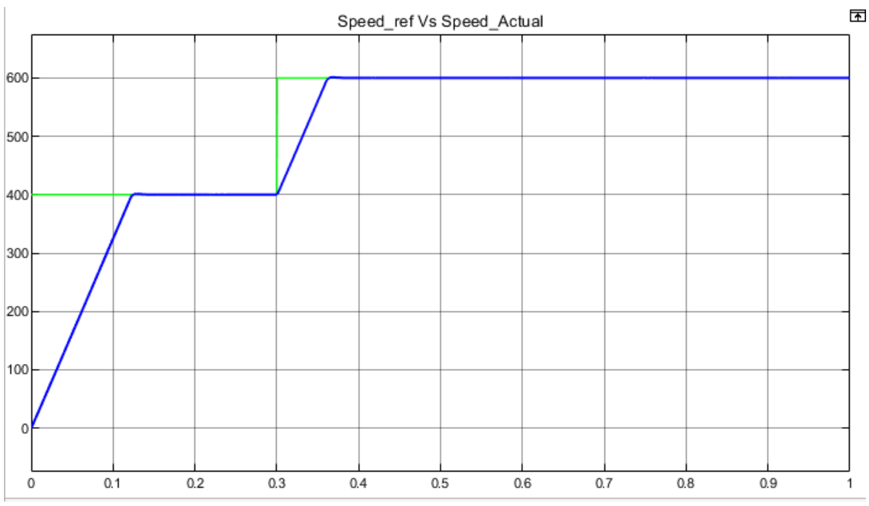
$$K_P = 0.642857$$

$$K_i = 76.5306$$

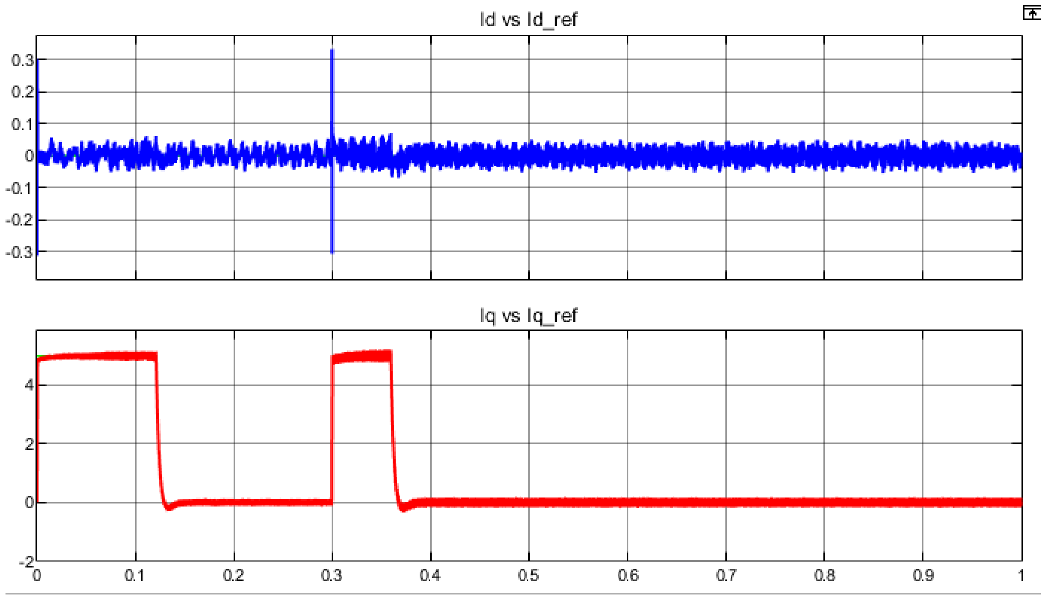


FOC Model for PMSM

- speed reference to start by 400 rpm then suddenly change to 600 rpm.



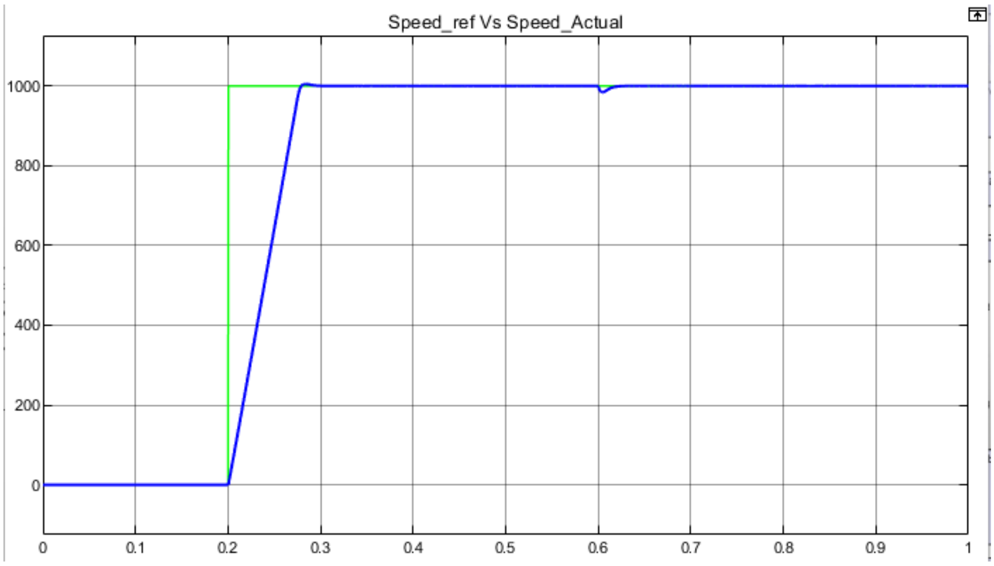
Speed Ref Vs Speed Actual



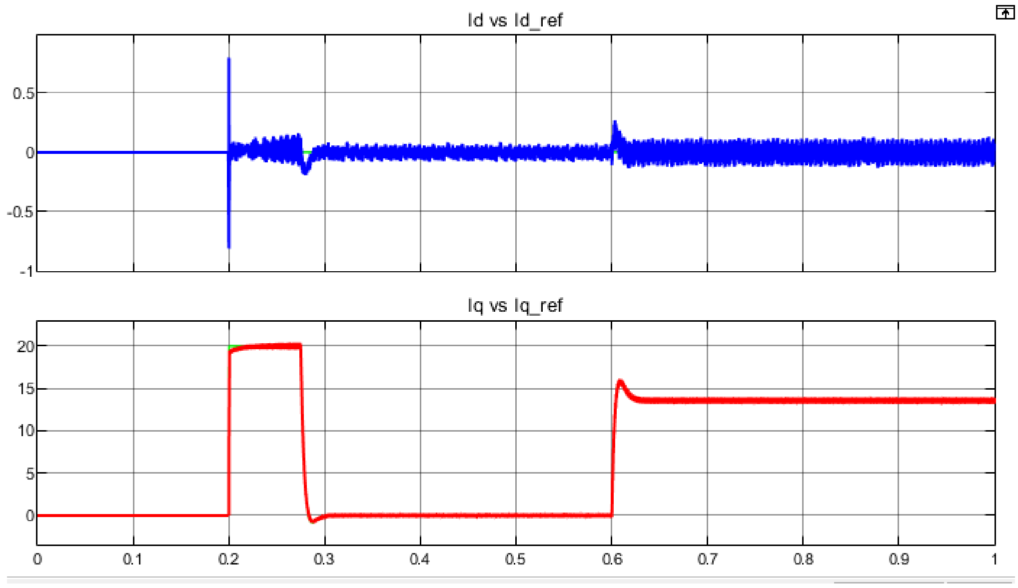
Id and Iq Vs Iq ref and Iq ref

The highest current iq is 4.65A, matching the base current. If we increase this value, the speed loop improves faster. This extra load, as long as the motor can handle it temporarily, won't harm the motor.

- step change in the load torque by 5 Nm at speed 1000 rpm

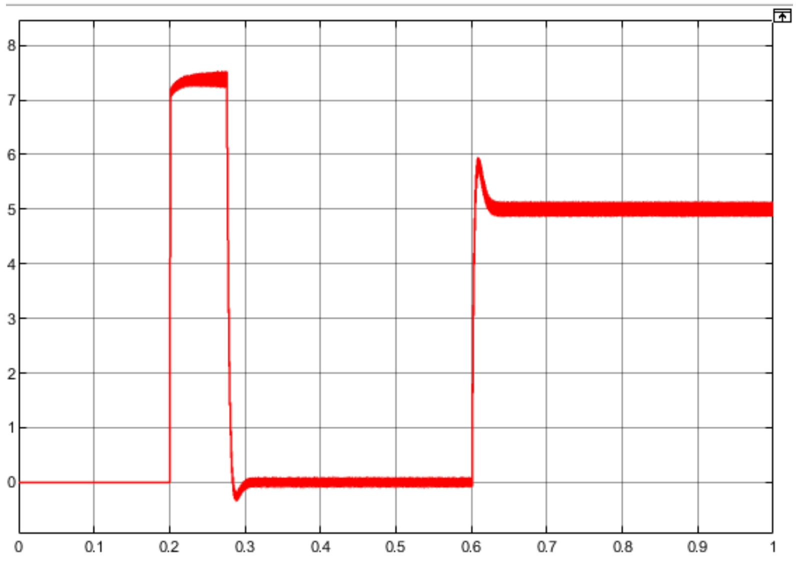


Speed Ref Vs Speed Actual step at 0.2 to 1000rpm



Id and Iq Vs Iq ref and Iq ref

We increase the limit of the Pi for speed loop to be 20 to make the motor able to achieve the 5 Nm load torque cause our motor rated torque is 2.43 Nm.



Motor Torque

Initially, the motor reaches its maximum torque limit, determined by the current limit from the speed loop's PI controller, in order to attain the desired reference speed. Subsequently, the iq drops back to zero, leading to a corresponding decline in torque. At time equal 0.6, a step external load torque of 5Nm is applied to the motor. As a result, the iq increases to align the torque output with the 5Nm load.