Analysis of Tesla Motor with Indirect Field Oriented Control

Overview

Indirect field oriented control is used to command the Tesla induction motor.

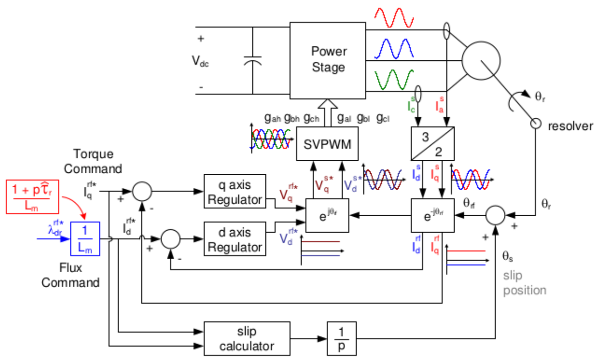


Fig. 1 . IFOC Overview

Synchronous Frame

Control is achieved by converting the stator currents to the synchronous reference frame.

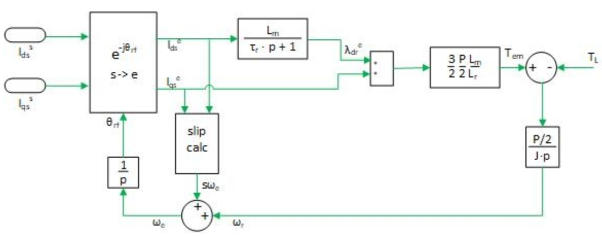


Fig. 2. Rotor Flux

Rotor flux is the integral of the combined slip frequency and rotor electric speed.

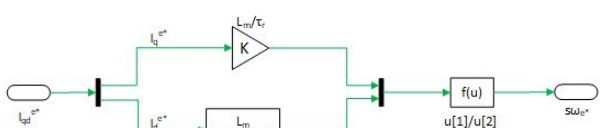


Fig. 3. Slip Calculation

Using rotor flux position, the stator currents are transformed to the synchronous frame such that they changing with the power supply. In this frame, the currents can be regulated to drive the induction motor.

Flux and Torque Commands

The flux command is maintained at a constant rated flux of 0.125 Wb. In the steady state response, the stator d-axis sync current is

$$I_{ds}^e = \frac{\lambda_{dr}^e}{L_m} \qquad .(1)$$

By keeping the d-axis flux constant, the motor can be driven with any torque command and the associated q-axis stator current. Max-rated toque is provided at 100N·m.

$$\begin{aligned} I_{qs}^e &= \frac{T_{em}}{K_t} \\ K_t &= \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} I_{ds}^e \end{aligned} \qquad (2)$$

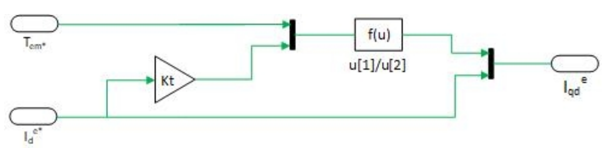


Fig. 4. Commanded Stator Currents

In Figure 4, K_t is rewritten as $K_t = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r}$.

Current Regulator

The induction motor receives space vector PWM voltages that are determined by the IFOC regulator. The sync stator voltages supplied are summarized as

$$\begin{aligned} v_{qs}^e &= (r_s' + \sigma L_s p) i_{qs}^e + (\sigma L_s \omega_e + \frac{L_m^2}{Lr}\omega_r) i_{ds}^e \\ v_{ds}^e &= (r_s + \sigma L_s p) i_{ds}^e - \sigma L_s \omega_e i_{qs}^e \\ r_s' &= r_s + \frac{L_m^2}{L_r} r_r \end{aligned} \qquad (3)$$

Similar to current regulator of a DC motor, the gains are solved using zero/pole cancellation at locked rotor conditions. This approach decouples sync frame and back emf effects.

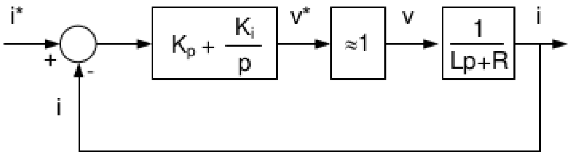


Fig. 5. DC Current Regulator

Then substitute the equivalent induction motor parameters.

	K_i	K_p
q-axis	$2\pi f_d r'_s$	$2\pi f_d \sigma L_s$
d-axis	$2\pi f_d r_s$	$2\pi f_d \sigma L_s$

Table 1: Tesla Current Regulator Gains

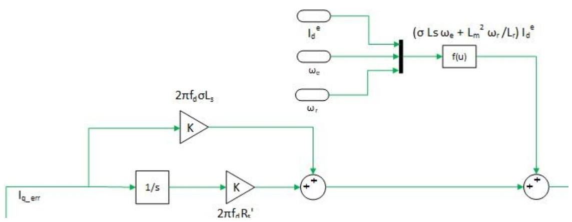


Fig. 6. Q-Axis PI Controller
with Sync Frame Coupling and Back EMF

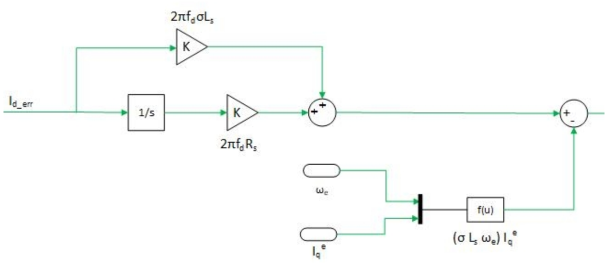


Fig. 7. D-Axis PI Controller
with Sync Frame Coupling

The q and d axis regulators are tuned to 1kHz bandwidths such that $f_d = 1000$. Note, the back EMF only effects the q-axis current.

Tem Step with Locked Rotor

Step command of a 100N·m is applied at 0.25 seconds. Commands are denoted with *.

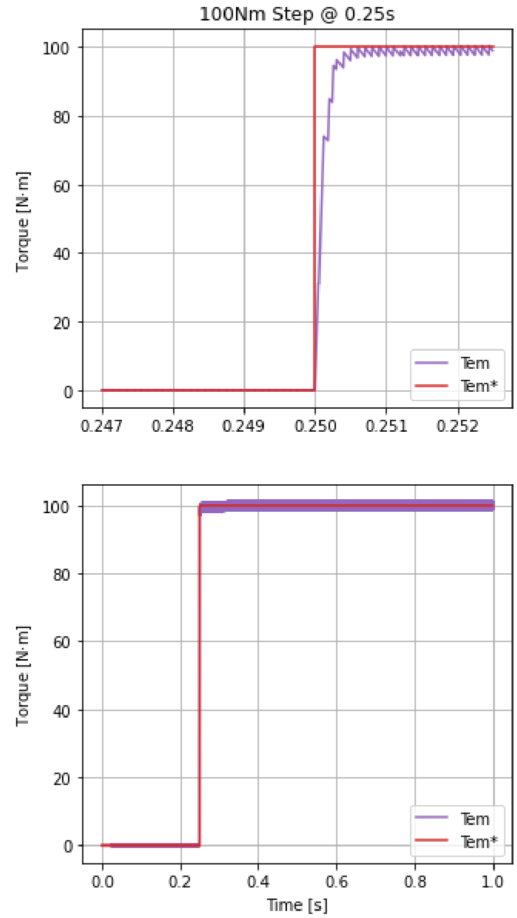


Fig. 8. T_{em} Step Response: Locked

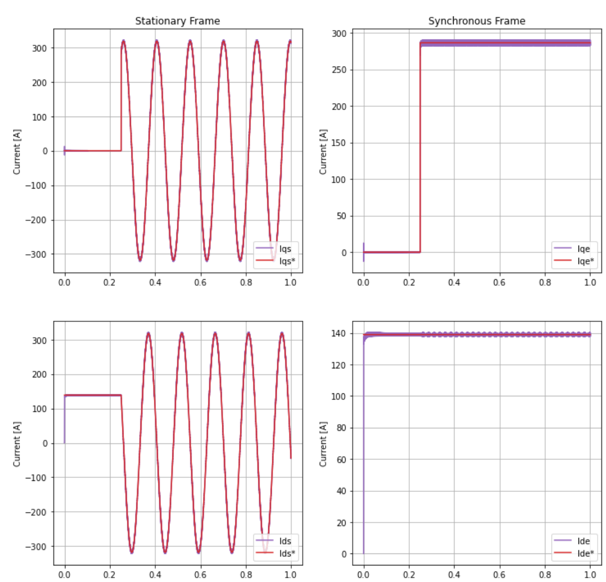


Fig. 9. Current Step Response: Locked

Tem Sine with Locked Rotor

Sine waves at 10Hz, 100Hz, 1000Hz are applied with rated toque and locked rotor.

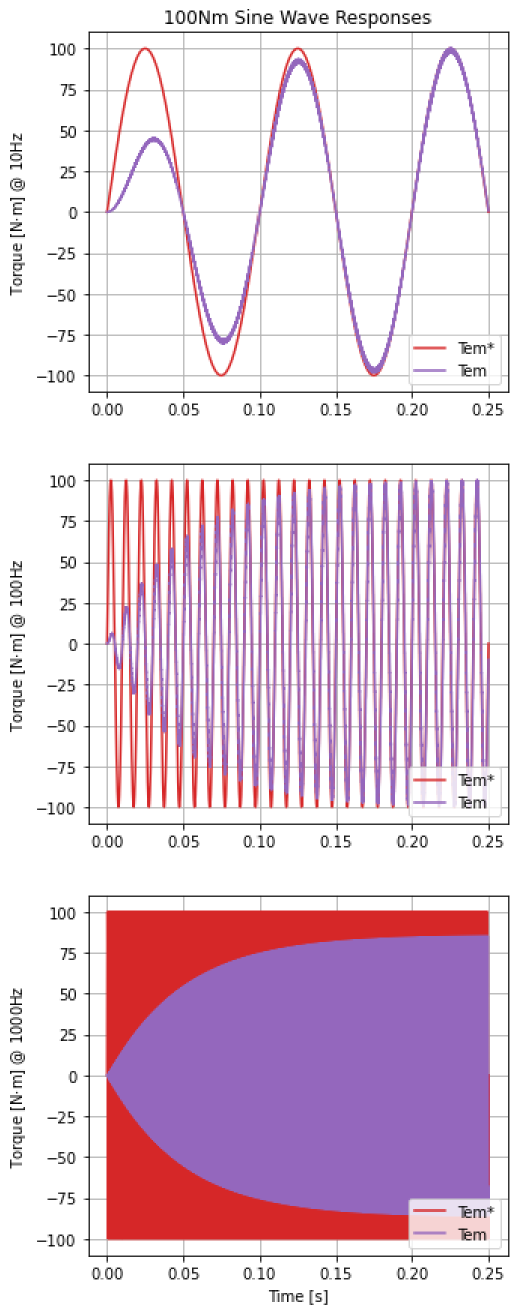


Fig. 10. T_{em} Sine Wave Response: Locked

Measured responses agree at 10Hz and 100Hz. However, at 1000Hz the measured torque envelope ramps to max value of ~85 N·m.

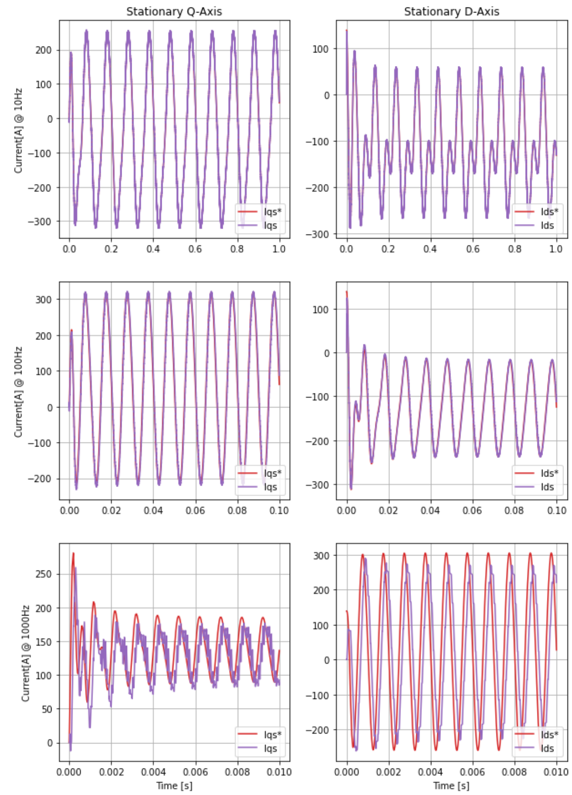


Fig. 11. Stationary Current Response: Locked

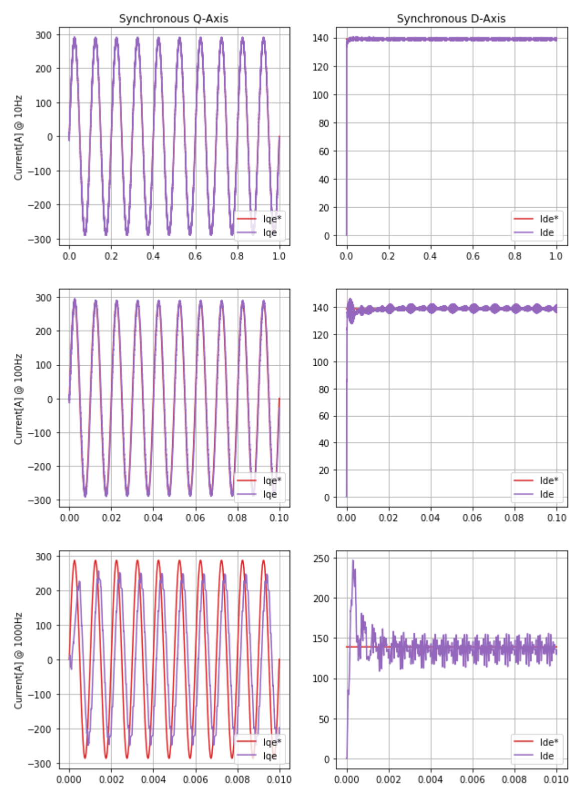


Fig. 12. Sync. Current Response: Locked

Speed Control

Speed control of the Tesla motor is identical to DC machines with ideal torque regulators.

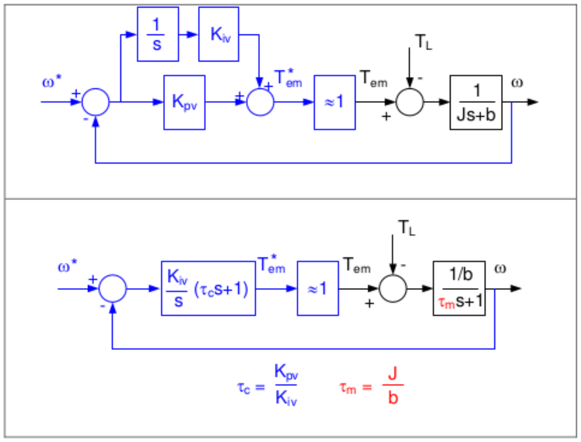


Fig. 13. DC Machine Speed Control

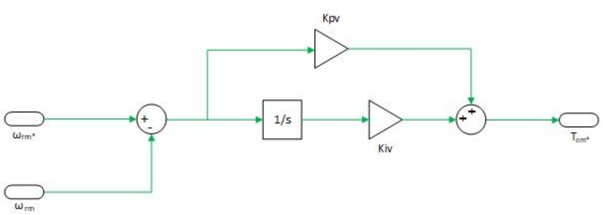
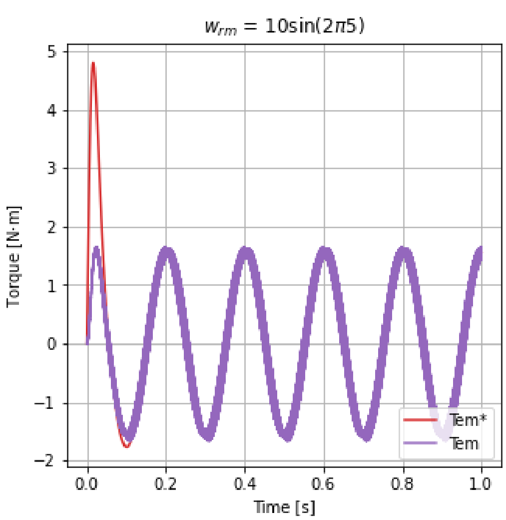


Fig. 14. Tesla Speed PI Controller

The gains are solved and tuned to 50Hz bandwidth.

K_i	K_p
$2\pi f_d b$	$2\pi f_d J$

Table 2: Tesla Speed Loop Gains



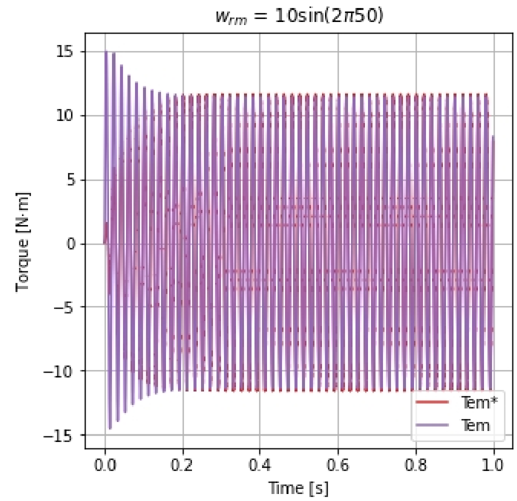


Fig. 14. Torque Response from Speed Cmd: Unlocked Rotor

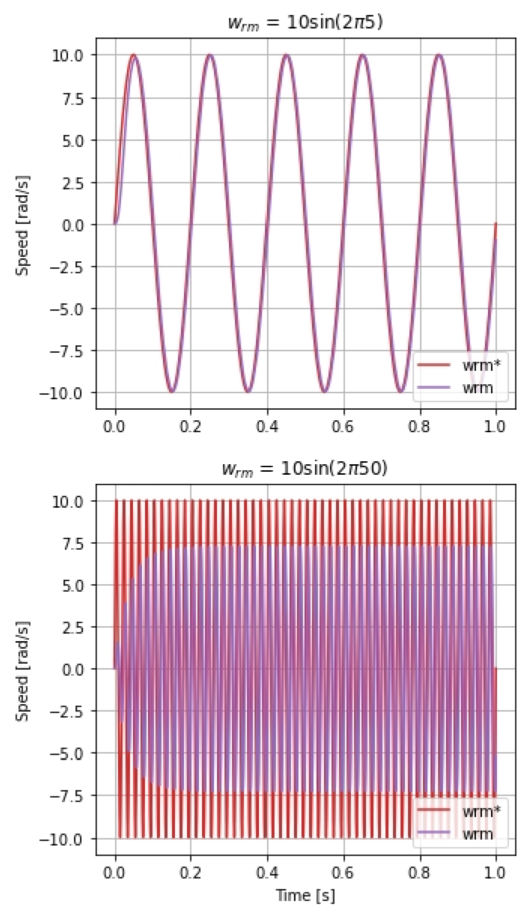
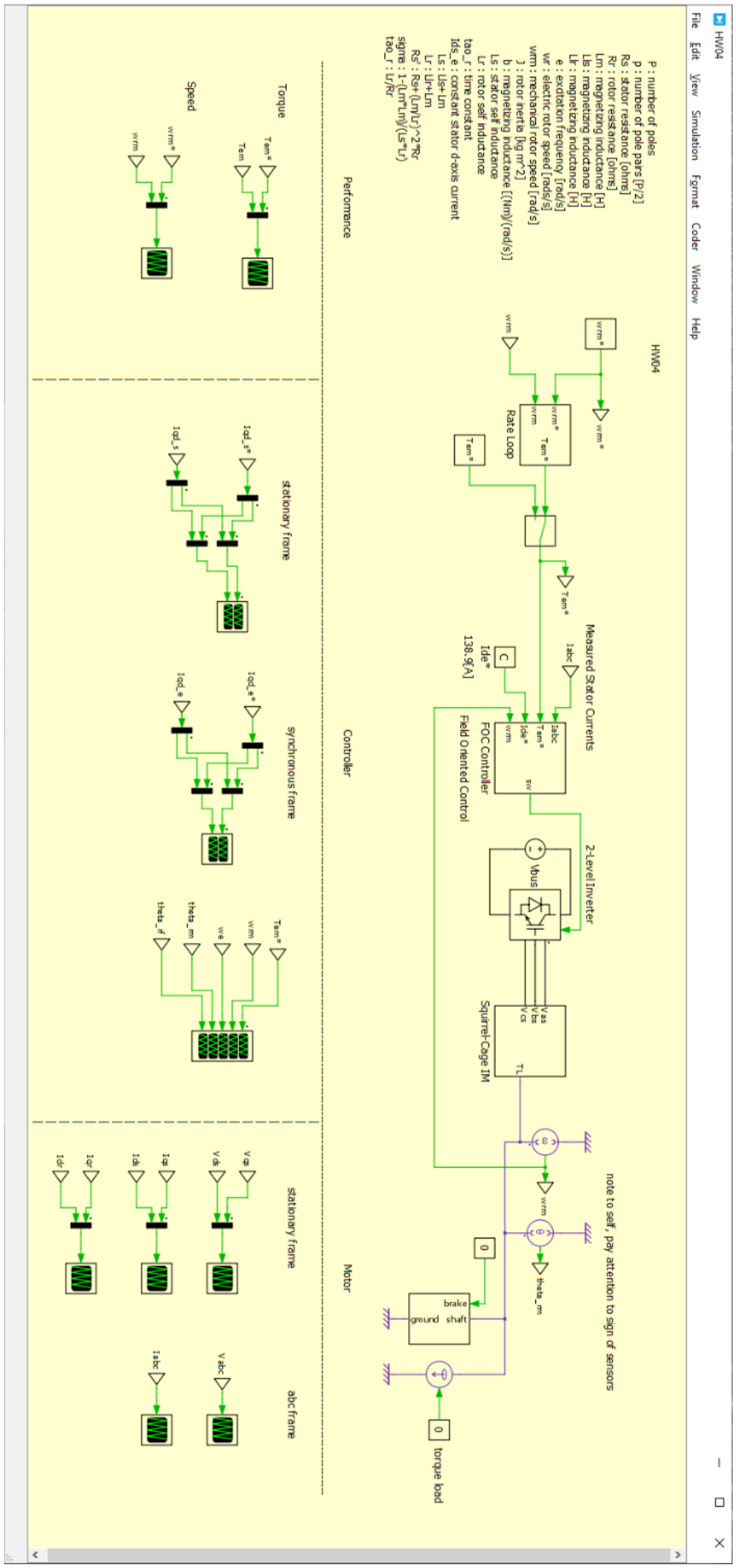


Fig. 15. Speed Response from Speed Cmd: Unlocked Rotor

As expected, the measured magnitude is -3dB less than the commanded at 50Hz.

Appendix


HW04
Rate Loop
Measured Stator Currents
138.9[A]
FOC Controller
Field Oriented Control
2-Level Inverter
Squirrel-Cage IM
note to self, pay attention to sign of sensors
torque load
Performance
Controller
Motor
Torque
Speed
stationary frame
synchronous frame
stationary frame
abc frame