Final Project: TESLA Induction Machine Controller

University of Washington
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Contents

1 Abstract

A TESLA induction machine (IM) is simulated using PLECS. Estimates of induction machine parameters are provided in Appendix A. A schematic of the controller is shown in Figure 1.

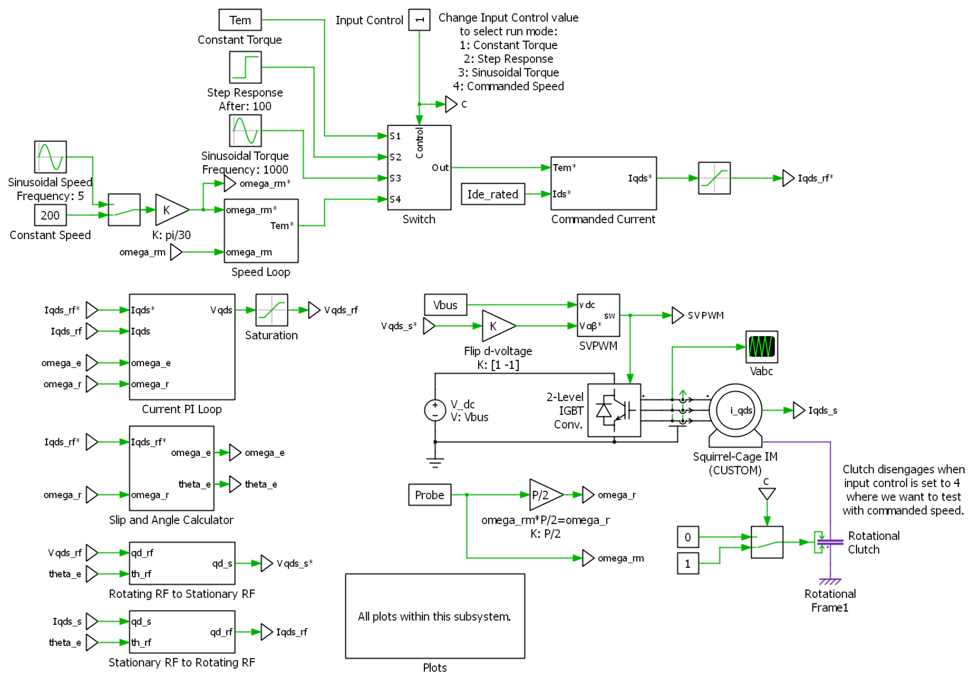

Figure 1: A top-level schematic of the TESLA IM simulation in PLECS. The various control scenarios can be seen in the upper-left region of this schematic.

The IM is simulated using indirect field oriented control. That is, instead of providing three-phase current, the current is provided in the d-q plane and only transformed to three-phase to input into the inverter that provides voltage to the IM.

The following control scenarios are simulated using a constant current with a PI loop:

- using a constant torque
- using a step response for the torque
- using a sinusoidal torque

The following control scenarios are simulated with the addition of a speed PI loop providing torque control:

- using a constant speed command
- using a sinusoidal speed command

Each control scenario is explained in detail and plots of results are provided and discussed.

2 Methods

A simplified overview block diagram of the simulation is shown in Figure 2. Stepping through the diagram beginning at the top-left corner, each block is detailed within this section.

1. **Speed Loop**: takes a commanded speed and outputs commanded torque T_{em}^*
2. **Current Command**: takes commanded torque and calculates command current $I_{qds}^{\text{rf}*}$
3. **Current Loop**: a PI loop that regulates d and q currents, outputing command voltage $V_{qds}^{\text{rf}*}$
4. **RRF to SRF**: converts the command voltage from the rotating frame to the stationary frame, producing V_{qds}^{s*}
5. **Space Vector PWM**: generates the inverter control signal for the IGBT Converter
6. **IGBT Converter**: outputs three phase PWM voltage for the IM
7. **IM**: outputs the response current I_{qds}^{s} and we also measure the speed ω_r
8. **SRF to RRF**: converts the response current from stationary to rotating frame, I_{qds}^{rf}
9. **Slip and Angle**: calculates the rotating frame angle θ_e needed by the two Park Transformation blocks, RRF to SRF and SRF to RRF

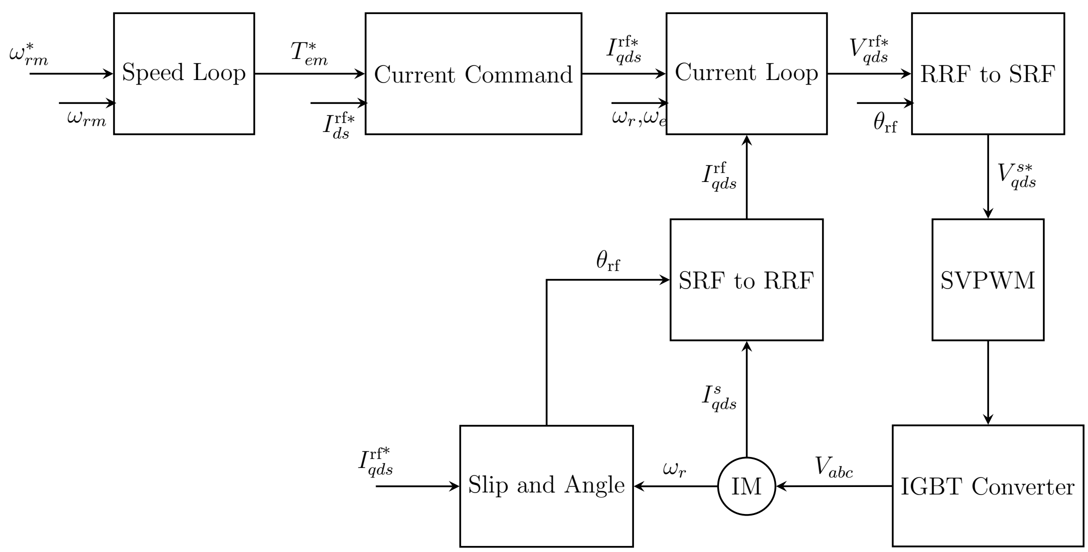

Figure 2: A simplified block diagram of the TESLA IM and the indirect field orientation control.

To better detail the circuit, each block is covered in detail in the following sections.

2.1 Speed Loop

The simulation circuit for the Speed Loop is shown in Figure 3. It is worth noting that the integrator and the gain K_{i_ω} can be swapped since the gain is a constant value.

2.1.1 Tuning

The tuning of the speed loop is done with a basic PI loop, as shown in Figure 3. The mechanical equivalent to the electrical PI loop is done with viscous damping b in place of the resistor as the

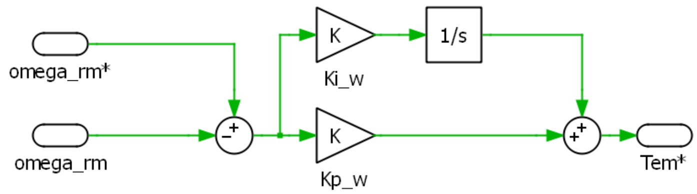

Figure 3: The Speed Loop block from the simulation.

disipitive element and inertia J in place of the inductor as the energy storage element:

$$K_{i\_\omega} = 2\pi f_{\text{desired}} b$$
$$K_{p\_\omega} = 2\pi f_{\text{desired}} J$$

The results of tuning at 50 Hz bandwidth:

$$f_{\text{desired}} = 50 \text{ Hz}$$
$$K_{i\_\omega} = 0.031416$$
$$K_{p\_\omega} = 1.5708$$

2.2 Current Command

The commanded current is constant for I_{ds} which is calculated using available provided flux linkage $\lambda_{dr}^{\text{rf}*}$ and mutual inductance L_m:

$$\lambda_{dr}^{\text{rf}*} = 0.125 \text{ Wb}$$
$$L_m = 0.9 \text{ mH}$$
$$I_{ds}^{\text{rf}*} = \frac{\lambda_{dr}^{\text{rf}*}}{L_m} = 138.9 \text{ A}$$

The two constants and the calculated value are provided with the problem statement. The calculated current is provided as $I_{\text{de\_rated}}$.

The q-current $I_{qd}^{\text{rf}*}$ is then calculated using the relationship with commanded torque T_{em}^*:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} I_{ds}^{\text{rf}*} I_{qs}^{\text{rf}*}$$
$$\therefore I_{qs}^{\text{rf}*} = T_e \frac{2}{3}\frac{2}{P}\frac{L_r}{L_m^2}\frac{1}{I_{ds}^{\text{rf}*}}$$
$$\therefore I_{qs}^{\text{rf}*} = \frac{4 T_e L_r}{3 P L_m^2 I_{ds}^{\text{rf}*}} \tag{E.1}$$

The result in (E.1) can be seen in the simulation circuit diagram for the Current Command block shown in Figure 4.

2.3 Current Loop with Indirect Field Oriented Control

The current loop is used to regulate the commanded current using negative feedback from the response current of the machine in a PI loop which is augmented by a Synchronous Frame Coupling factor and

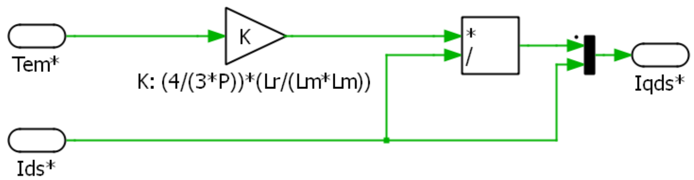

Figure 4: The Current Command block from the simulation.

an approximation of Back EMF. [1]

$$v_{qs}^e = (r_s' + \sigma L_s p) i_{qs}^e + \left(\sigma L_s \omega_e + \frac{L_m^2}{L_r}\omega_r\right) i_{ds}^e$$
$$v_{ds}^e = (r_s + \sigma L_s p) i_{ds}^e - \sigma L_s \omega_e i_{qs}^e$$

where

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \rightarrow \text{coupling factor}$$
$$r_s' = R_s + \left(\frac{L_m}{L_r}\right)^2 R_r$$

When put into block form, these equations produce the Current Loop block shown in Figure 5.

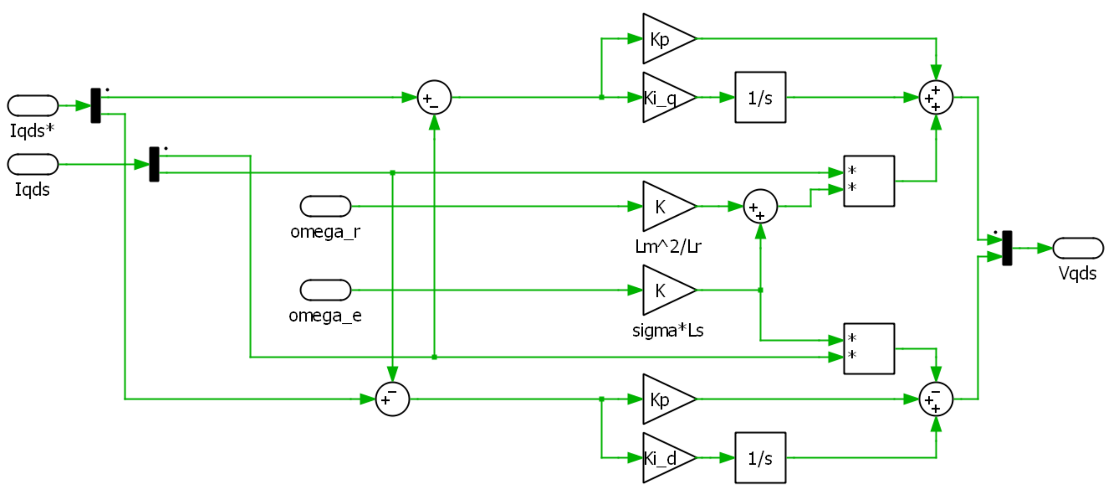

Figure 5: The Current Loop block from the simulation.

2.3.1 Tuning

Tuning a DC current loop produces the following gains:

$$K_p = 2\pi f_{\text{desired}} R_a$$
$$K_i = 2\pi f_{\text{desired}} L_a$$

[1]The full derivation is provided in class notes Lecture 9.

In the induction machine, the same general equations can be used provided with a few changes where the coupling factor applies to the q-current but not the d-current:

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}$$
$$r_s' = R_s + \left(\frac{L_m}{L_r}\right)^2 R_r$$
$$K_p = 2\pi f_{\text{desired}} R_s'$$
$$K_{i\_q} = 2\pi f_{\text{desired}} \sigma L_s$$
$$K_{i\_d} = 2\pi f_{\text{desired}} L_s$$

These values are calculated within the simulation parameters section with a desired bandwidth of 1000 Hz:

$$f_{\text{desired}} = 1000 \text{ Hz}$$
$$K_p = 0.81043$$
$$K_{i\_q} = 203.15$$
$$K_{i\_d} = 94.248$$

2.4 Rotating RF to Stationary RF

The RRF to SRF block is a Park Transformation of the voltage in the rotational reference frame to the stationary reference frame. The transformation uses the following function:

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} v_{qs}^{\text{rf}} \\ v_{ds}^{\text{rf}} \end{bmatrix}$$

The schematic from the simulation, shown in Figure 6 uses functions and vectors to accomplish the transformation.

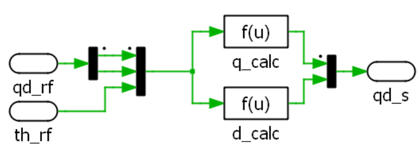

Figure 6: The RRF to SRF block from the simulation.

2.5 Space Vector PWM and Inverter

The Space Vector PWM block generates a voltage vector according to a reference signal from the stationary reference frame. This helps explain why we must use Park's Transformation to convert $V_{qds}^{\text{rf*}}$ to V_{qds}^{s}.

The three-phase generated voltage vector is used as input to the IGBT Converter. The IGBT Converter is a three-phase two-level converter. It outputs the $+V_{dc}$ value if the input is ¿ 0, the $-V_{dc}$ value fi the input is ¡ 0, and nothing at all if the control input is == 0. Since the IGBT Converter is only two-level, cycling back and forth between $+V_{dc}$ and $-V_{dc}$, it provides a PWM voltage to drive the IM.

2.6 Squirrel-Cage Induction Machine

The Squirrel-Cage IM used in this assignment is the one that was designed in a previous homework assignment. Given a three-phase input, this custom Squirrel-Cage IM first converts it to a d-q voltage signal using Clarke's Transformation and then proceeds to calculate the I_{qds}, flux linkages, I_{qdr}, and the generated torque T_e.

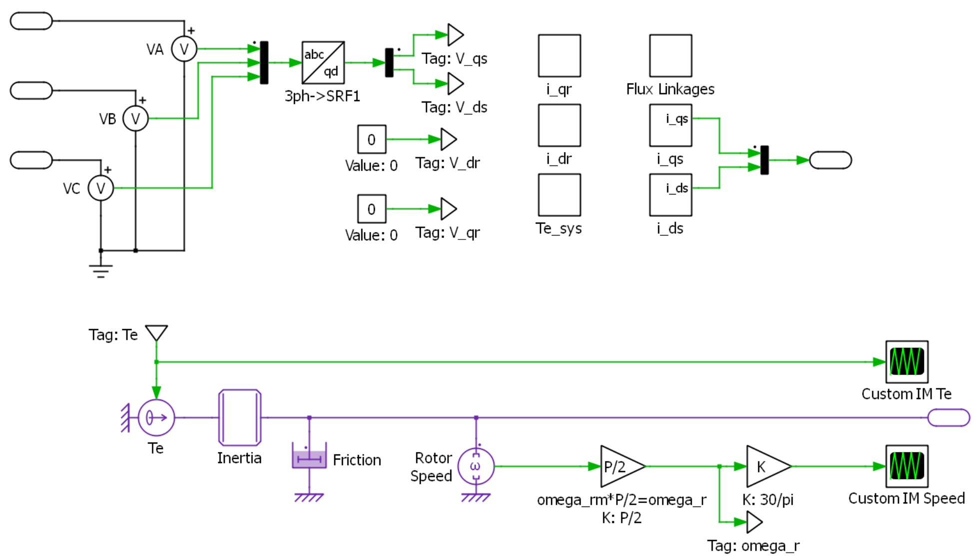

Figure 7: The schematic of the custom Squirrel-Cage IM.

2.6.1 Clarke's Transformation

While the built-in PLECS Squirrel-Cage IM uses electrical wires for its model, our custom design only manipulates signals. This means that there is actually no current flowing into the custom Squirrel-Cage IM. Therefore, the response current is always zero when using the custom IM.

The solution, found while working with Ahmad, not only provides the needed response current but reduces circuit complexity by eliminating the need for Clarke's Transformation altogether.

Since the custom Squirrel-Cage IM is already calculating I^{s}_{qds} as a signal, we output that signal directly from the IM and use it as the IM response current I^{s}_{qds}. Previously, we were measuring the three-phase I_{abc} current flowing into the IM and then using Clarke's Transformation to convert it to the q-d realm.

Although this eliminates the need to use Clarke's Trasnformation on the measured currents, it is worth noting that the custom IM is already doing Clarke's transformation on the measured voltages.

2.7 Stationary RF to Rotating RF

The SRF to RRF block is a Park Transformation of the current in the stationary reference frame to the rotational reference frame. The transformation uses the following function:

$$\begin{bmatrix} i^{\mathrm{rf}}_{qs} \\ i^{\mathrm{rf}}_{ds} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i^{s}_{qs} \\ i^{s}_{ds} \end{bmatrix}$$

The schematic from the simulation, shown in Figure 8 uses functions and vectors to accomplish the transformation.

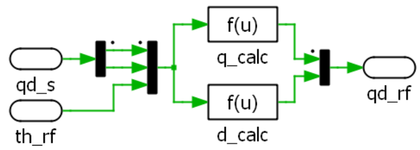

Figure 8: The SRF to RRF block from the simulation.

2.8 Slip and Angle

The slip-frequency is calculated in the Slip and Angle block and then used directly to calculate the speed. Integrating the speed provides the angular position θ_{rf} in the rotating reference frame. This stems from the slip relationship for field orientation:

$$
\begin{aligned}
s &= \frac{\omega_e - \omega_r}{\omega_e} \\
\therefore s\omega_e &= \omega_e - \omega_r \\
\therefore s\omega_e + \omega_r &= \omega_e \\
s\omega_e &= \frac{1}{\tau_r}\frac{I_{qs}}{I_{ds}}
\end{aligned}
$$

The resulting equation can be seen in block form for the simulation in Figure 9.

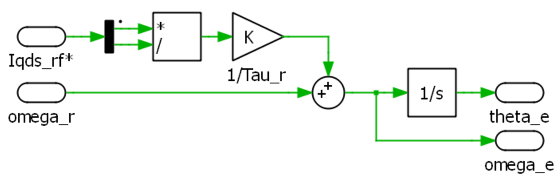

Figure 9: The Slip and Angle block from the simulation.

3 Simulation: Commanded Torque

With a locked rotor and constant d-axis, three separate commanded torque scenarios are presented:

1. Constant Torque
2. Step Response
3. Frequency Response via 10 Hz, 100 Hz, and 1000 Hz sinusoidal torque

3.1 Constant Torque

Constant Torque is simulated in the model by setting the "Input Control" signal to 1. The resulting plots for I_{qds}^{rf*} are shown in Figure 10. The command current is not visible because the current ripple in the response current ends up hiding it.

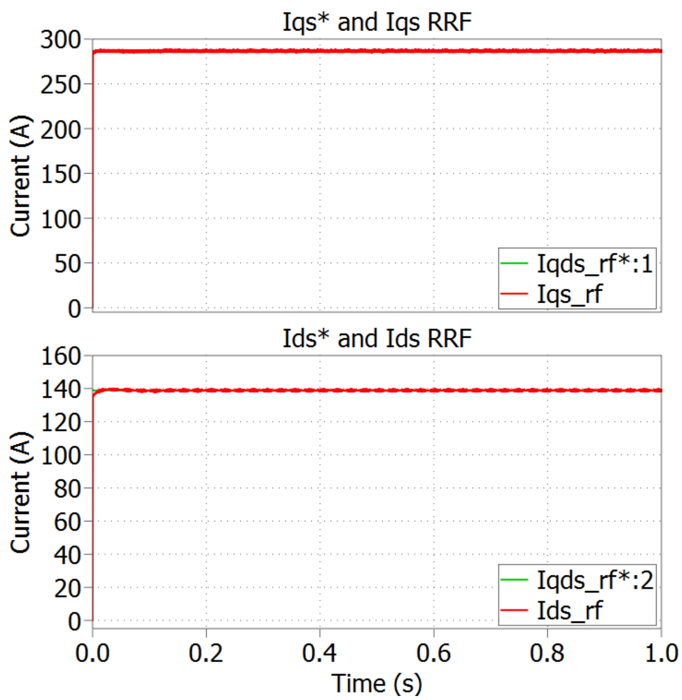

Figure 10: The current command (green) and response (red) for a constant commanded torque.

3.2 Step Response

A Step Reponse is simulated in the model by setting the "Input Control" signal to 2. This particular step response is set to command 100 N-m of torque at 0.5 seconds. The resulting plots are shown in Figure 11.

Again, the commanded current is not visible because the response current rippple covers it up. There is a slight green mark for the constant $I_{ds}^{\text{rf}*}$ shown in the lower plot of Figure 11 at 138.9 Amps.

While $I_{ds}^{\text{rf}*}$ is held constant, $I_{qs}^{\text{rf}*}$ starts at 0 and only jumps up when the step response kicks in for the 100 N-m of torque. The current ripple becomes pronounced at precisely that time as well.

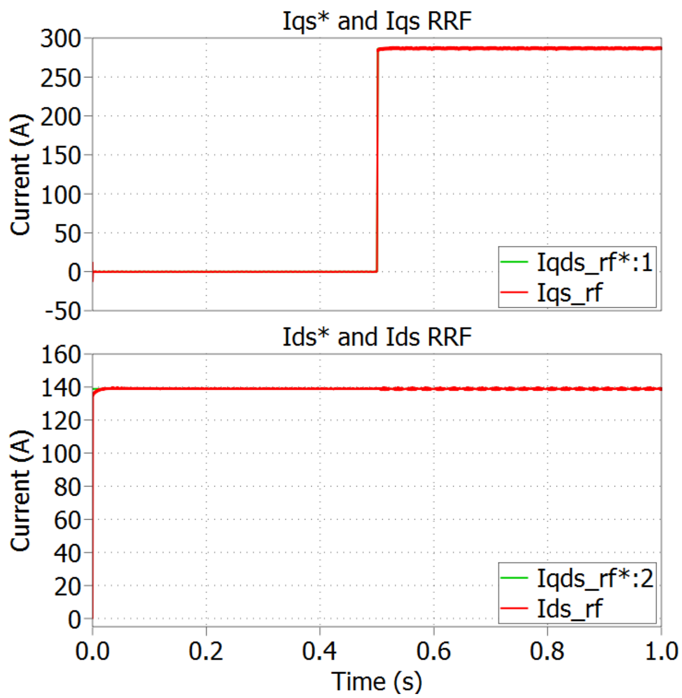

Figure 11: The current command (green) and response (red) for a step response commanded torque.

3.3 Sinusoidal Torque

The Sinusoidal Torque is simulated in the model by setting the "Input Control" signal to a 3. The results for commanded and response currents at 10 Hz, 100 Hz, and 1000 Hz are shown in Figure 12, Figure 13, and Figure 14 respectively.

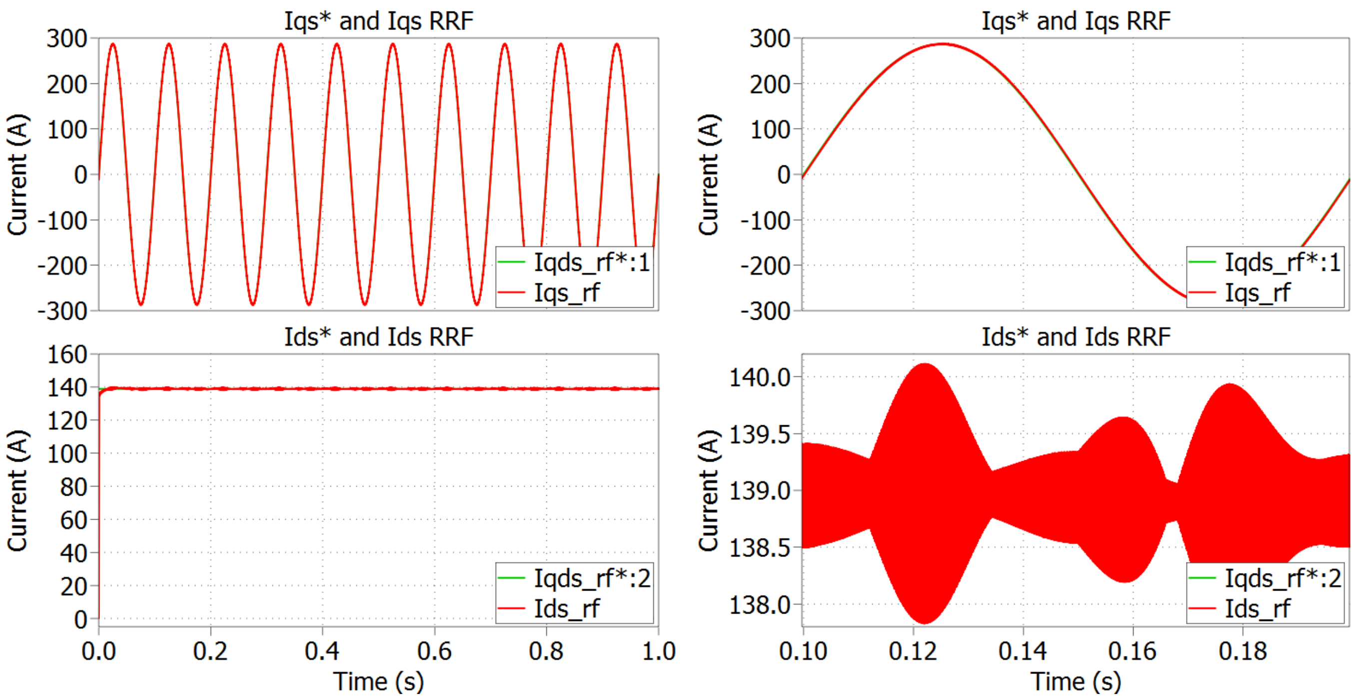

Figure 12: The current command (green) and response (red) for sinusoidal torque input at 10 Hz. A full second is shown on the left and a single period on the right. The current ripple spans 2.2 Amps.

As expected, the reponse current in Figure 14 is attenuated to commanded current times $\frac{1}{\sqrt{2}}$ when the commanded torque frequency is 1000 Hz which is what the current loop is tuned to.

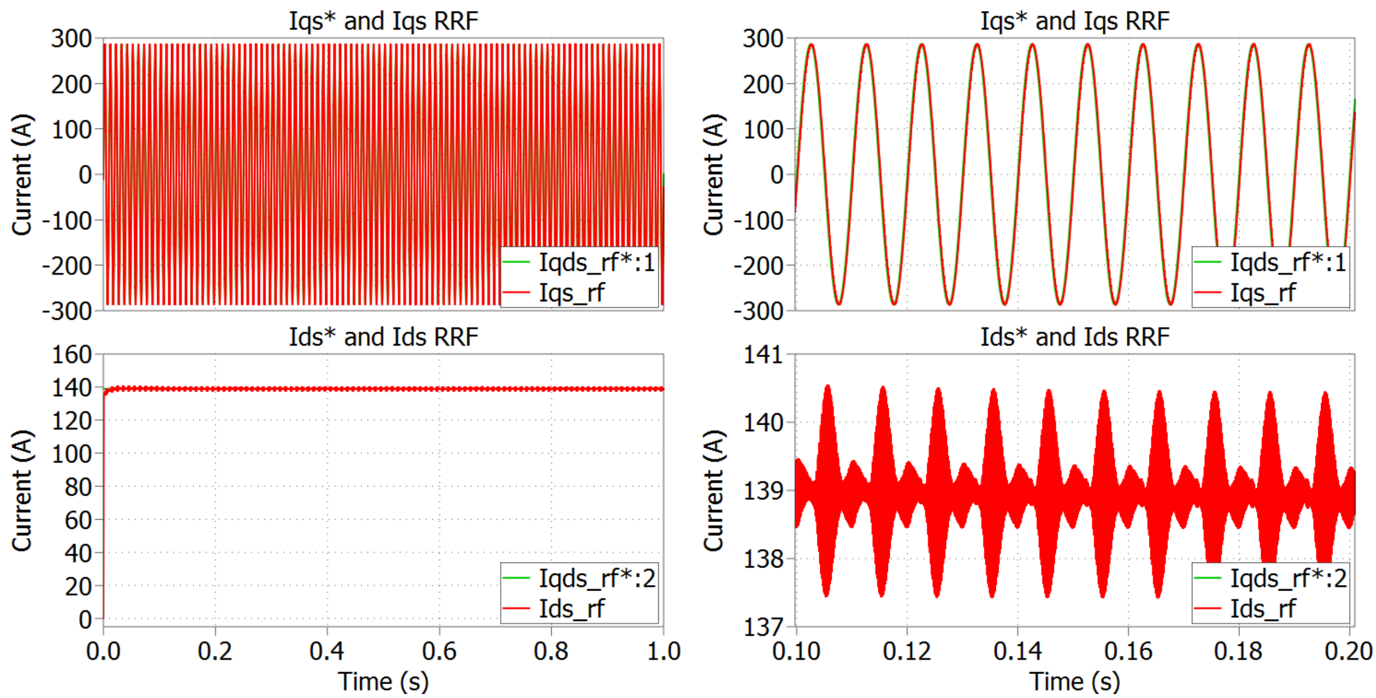

Figure 13: The current command (green) and response (red) for sinusoidal torque input at 100 Hz. A full second is shown on the left and a few periods on the right. The current ripple spans 2.2 Amps.

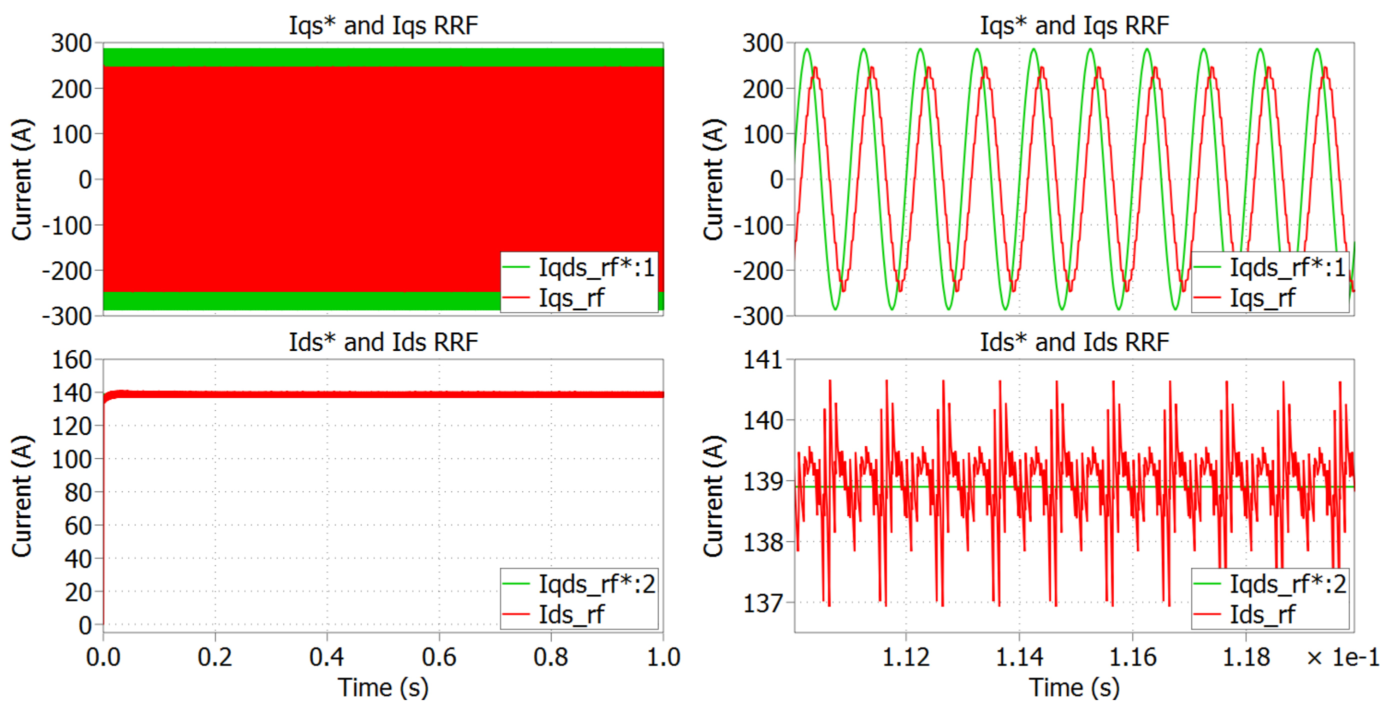

Figure 14: The current command (green) and response (red) for sinusoidal torque input at 1000 Hz. A full second is shown on the left and a few periods on the right. The response current is $\frac{1}{\sqrt{2}}$ times the commanded current since the frequency is equal to the bandwidth.

4 Simulation: Commanded Speed

The speed loop is turned on by setting the "Input Control" to 4. This also disengages the clutch on the IM as explained in Appendix B which allows the shaft to spin freely.

4.1 Constant Speed

Using a constant speed of 200 rpm, the current and speed plots are shown in Figure 15.

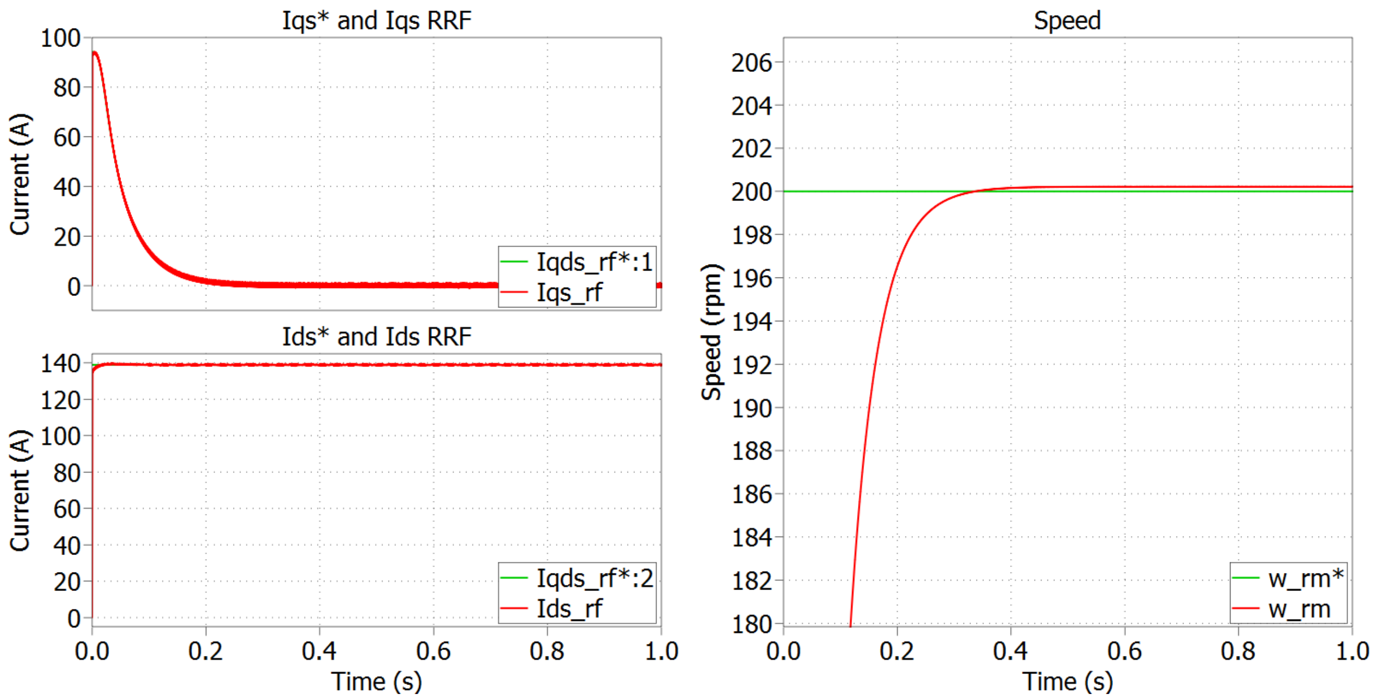

Figure 15: The current command (green) and response (red) for constant commanded speed input (left) and resonse speed (right).

The commanded speed is easier to see on the speed plot than commanded current is on the current plots. The speed reaches the commanded 200 rpm at approximately 0.3 seconds. This is also the time when the current approaches zero. There is no need to look at a torque plot because we already know that the torque is proportional to the I_{qs}^{rf*} current which means a torque plot would almost identically match the current plot - aside from scale of numbers.

4.2 Sinusoidal Speed

Using a sinuisoidal speed command produces plots shown for 5 Hz in Figure 16 and 50 Hz in Figure 17. As expected, the signal attenuates by approximately 70.7% when the sinusoid is set at the tuned bandwidth of 50 Hz as shown in Figure 17.

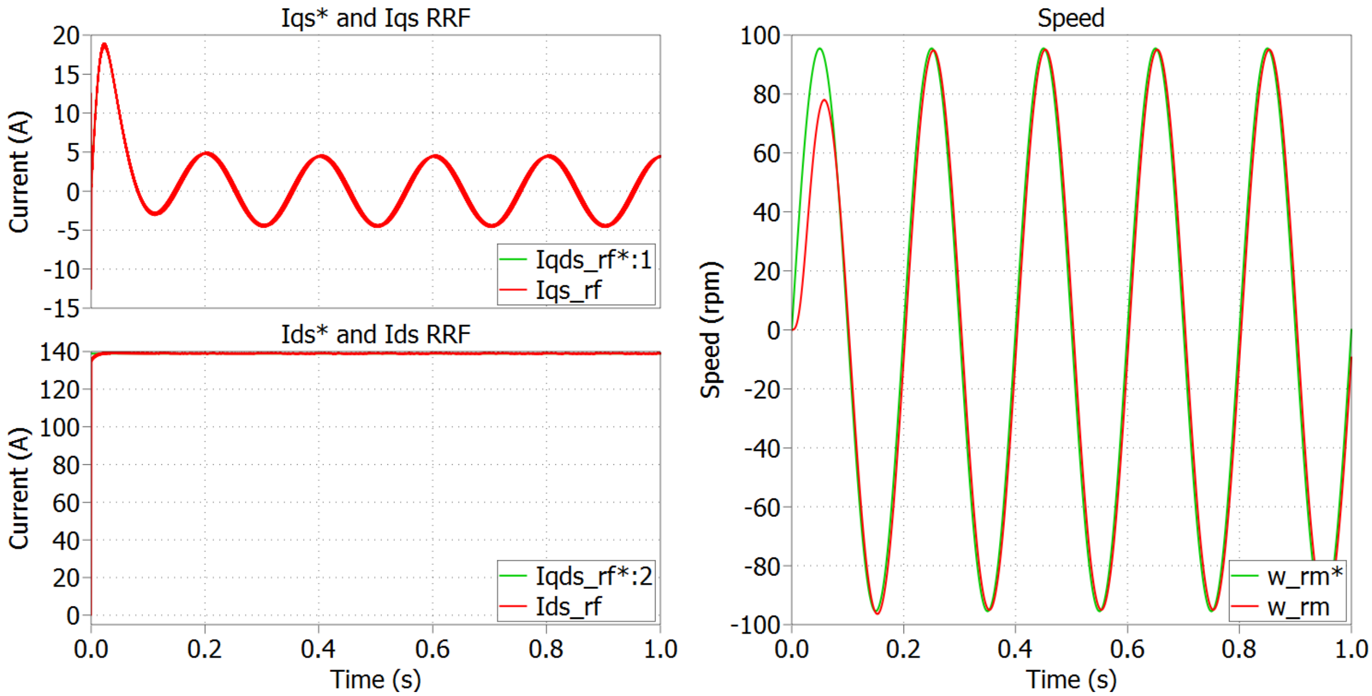

Figure 16: The current command (green) and response (red) for a 5 Hz sinusoidal speed command (left) and speed (right).

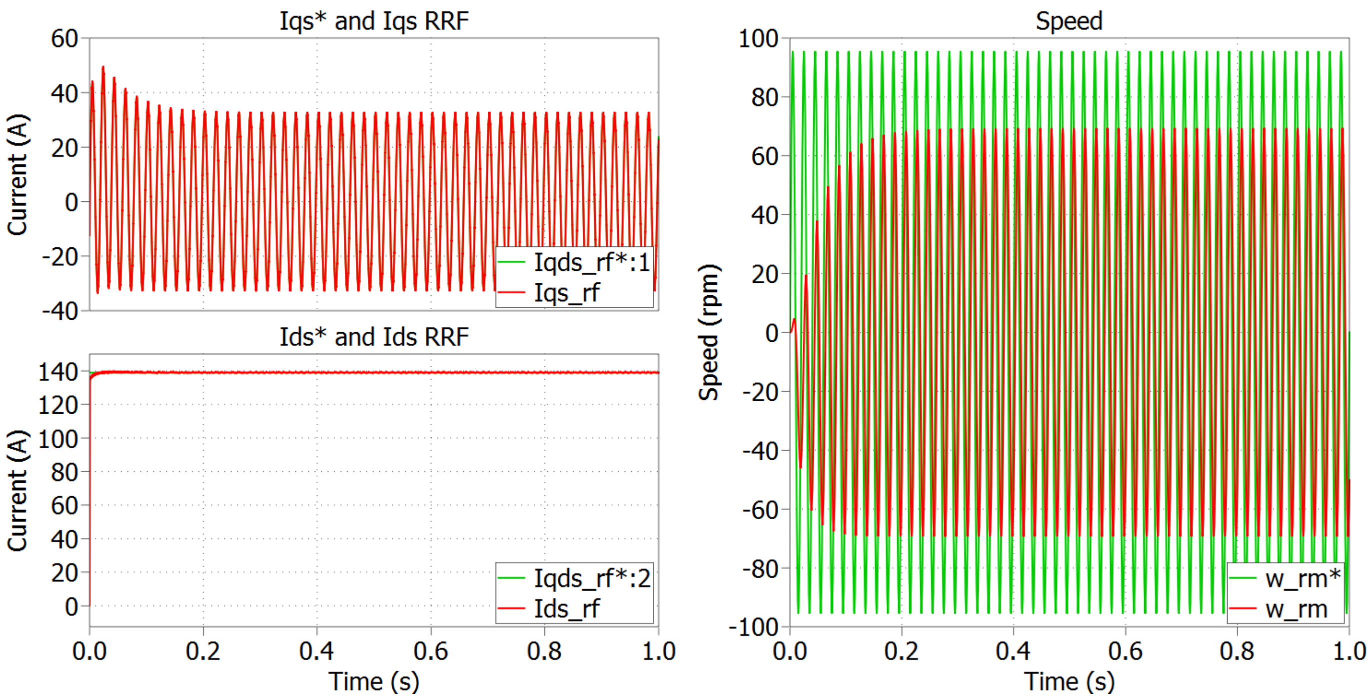

Figure 17: The current command (green) and response (red) for a 50 Hz sinusoidal speed command (left) and speed (right). The speed is being attenuated, as expected, since the frequency here is the same as the speed loop bandwidth.

5 Conclusions

The indirect field oriented control works very well. The current loop, tuned to 1000 Hz, behaves as expected as does the speed loop, tuned to 50 Hz.

This has been a very interesting project. I only got the project all functional a couple days before I am to turn it in leaving me almost no time for additional analysis. I wish I had time to go step-by-step over the derivation to gain a better understanding just how this was all made possible.

On the custom pieces, although I have not done additional analysis, there were a couple bright bits:

- The Input Control functionality which I wrote into my PLECS model makes it super easy for anyone else to run it and demonstrates how to control the torque of the machine with a clutch.
- Ahmad helped me discover that we could forgo the Clarke Transformation if we extracted I_{qds}^{s} directly from the custom IM.

5.1 Hindsight

I took this course despite knowing I would have a busy life schedule because the material is very interesting to me. While I did learn a lot, I could have learned more had I not had a newborn child at the same time. Even so, I learned a lot. Just noting to my future self who will reread this one day - you have limits and this term you reached them!

Appendix A IM Parameters

$P = 4$	number of motor poles
$R_s = 0.015\ \Omega$	stator resistance
$R_r = 0.020\ \Omega$	rotor resistance
$L_m = 0.9$ mH	mutual inductance
$L_{ls} = 0.0668$ mH	stator leakage inductance
$L_{lr} = 0.0668$ mH	rotor leakage inductance
$L_s = L_m + L_{ls}$	stator inductance
$L_r = L_m + L_{lr}$	rotor inductance
$J = 0.005$ kg-m^2	machine inertia
$b = 1.0 \times 10^{-4}\ \frac{\text{N-m}}{\left(\frac{\text{rad}}{\text{sec}}\right)}$	machine damping
$T_{\text{rated}} = 100$ N-m	rated machine torque
$\lambda_{\text{rated}} = 0.125$ Wb	rated machine flux
$I_{\text{de\_rated}} = 138.9$ A	rated d-axis current
$V_{\text{bus}} = 375$ V	bus voltage
$I_{\text{max}} = 350$ A	maximum motor current

Table A.1: TESLA IM parameters. Parameters are best guess as provided in assignment.

$\tau_r = \frac{L_r}{R_r}$	rotor time constant
$\sigma = 1 - \left(\frac{L_m^2}{L_s \cdot L_r}\right)$	coupling factor
$f_{\text{desired}} = 1000$ Hz	bandwidth of currrent controller
$K_p = 2\pi f_{\text{desired}} \sigma L_s$	proportional gain for current loop
$R_{s\_prime} = R_s + \left(\frac{L_m}{L_r}\right)^2 \cdot R_r$	relative resistance for current loop
$K_{iq} = 2\pi f_{\text{desired}} R_{s\_prime}$	q-signal integral gain for current loop
$K_{id} = 2\pi f_{\text{desired}} R_s$	d-signal integral gain for current loop

Table A.2: TESLA IM current control loop tuning parameters.

$f_{\text{desired}} = 50$ Hz	speed loop bandwidth
$K_{i\omega} = 2\pi f_{\text{desired}} b$	integral gain for speed loop
$K_{p\omega} = 2\pi f_{\text{desired}} J$	proportional gain for speed loop

Table A.3: TESLA IM speed control loop tuning parameters.

Appendix B PLECS Model Control

The PLECS model is provided as a zip attached to the file submission. The model is set up to be very easily used to try out all five simulation scenarios. Reviewing the full schematic from Figure 1, the important control sections are highlighted in Figure B.1. The "Switch" block is shown in Figure B.2.

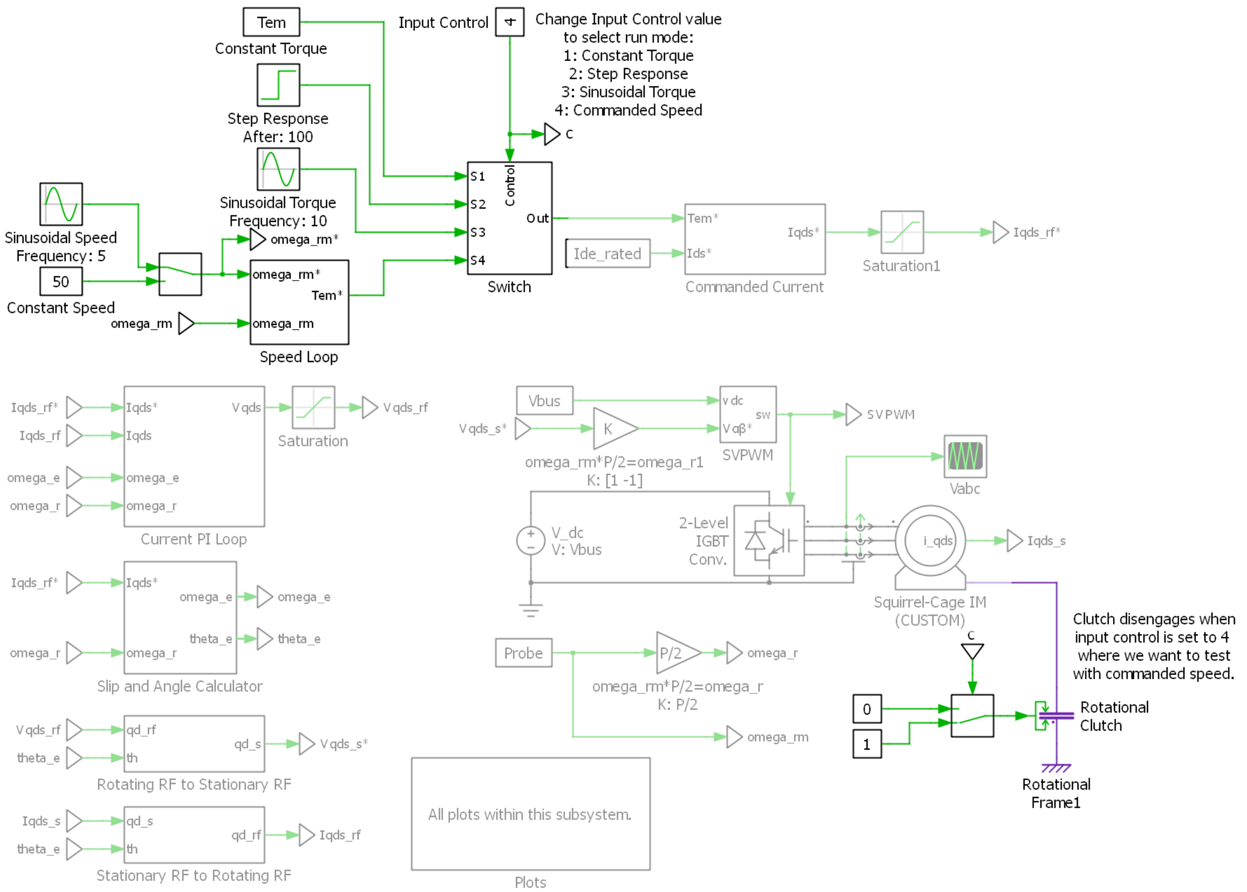

Figure B.1: The full system schematic from PLECS with the scenario control areas highlighted.

The constant labeled "Input Control" will switch which torque value to choose from with valid inputs as follows:

1. Constant Torque - defaults to 100 N-m
2. Step Response - defaults to 0 N-m until 0.5 seconds at which point 100 N-m is applied
3. Sinusoidal Torque - defaults to a frequency of 10 Hz with an amplitude of 100 N-m
4. Commanded Speed - this pulls from the Speed Loop which itself has two input options further controlled with a manual switch. The manual switch can be toggled by double-clicking it. It has two options:
   - Top: Sinusoidal Speed with a default frequency of 5 Hz and amplitude 10 rad/sec.
   - Bottom: Constant Speed with a default of 50 rad/sec

   Also noe that when the "Input Control" is set to 4 for Commanded Speed, the Rotational Clutch in the bottom-rith of the schematic disengages automatically freeing the IM from locked rotor.

All relevant plots are contained inside the "Plots" subsystem.

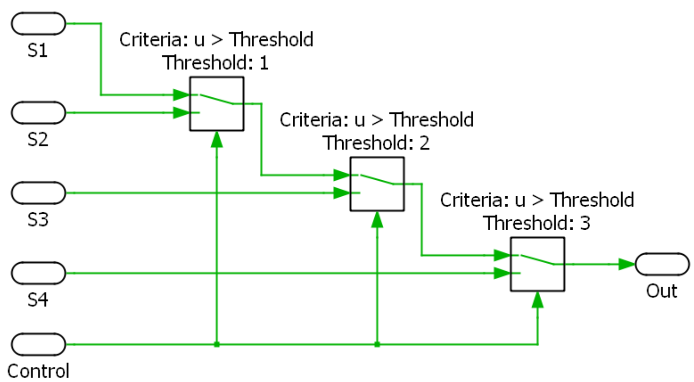

Figure B.2: The Switch block with controlled switches configured such that a 1 sends through S1, a 2 sends through S2, etc.