EEE223 (2023-2024)
Introduction to Electronic and Electrical Circuits

Sem1 - Assignment

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I, James Bray certify that I have neither given nor received any unauthorised aid in this assignment	
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Contents

Motor Specification

A 10 hp, 230-V (phase value), 50 Hz, Star-connected three-phase squirrel-cage induction motor is used as an air compressor in the airport workshop. The following data is taken from different manufacturers' datasheets, which are needed to select the appropriate data to build a MATLAB/SIMULINK code/model.

- The rated shaft power is 10 hp (1 hp = 746 W)
- Rotational loss is neglected
- The available phase voltage is 230 V
- The synchronous speed is in the range of 1400 to 1800 rpm.
- The full-load slip is 4.8 %.
- Take the stator resistance 0.8 Ω.
- Take the rotor resistance at a standstill of 0.8 Ω.
- Take the magnetising inductance 0.637 H.
- Take the stator leakage inductance equals the rotor leakage inductance.
- The motor inertia is 0.1 kg.m2
- The viscous motor friction or friction factor is neglected.

Analytical Solutions

1.1 Considering you can only have an even integer amount of poles, I will choose the number of poles first, then calculate the synchronous speed.

With 4 poles:

$$N_s = \frac{120 \cdot 50}{4} = 1500 rpm$$

With 6 poles:

$$N_s = \frac{120 \cdot 50}{6} = 1000 rpm$$

Therefore I am choosing a 4-pole motor with N_s of 1500 rpm as it is in range.

1.2 The full shaft torque is achieved when the motor is operating at 10 hp (7460 W)

$$N_r = N_s \cdot (1 - s) = 1428 rpm$$

$$\omega_r = N_r \cdot \frac{2\pi}{60} = 149 rads^{-1}$$

$$T_{FL} = \frac{P}{\omega_r} = 49.89 Nm$$

1.3 Finding the stator current at the selected full load slip:

$$P_d = s \cdot I_r^{\,2} \cdot \frac{R_r \cdot (1 - s)}{s} \quad \Rightarrow \quad I_r = 12.52A$$

$$\varphi_r = -\tan^{-1}\left(\frac{\left(X_s + X_r\right)}{\left(R_s + \frac{R_s}{s}\right)}\right) = -18.04°$$

$$I_m = \frac{V_s}{2\pi \cdot \mathrm{f} \cdot \mathrm{L_m}} = -1.15A \quad \Rightarrow \quad I_0 = -1.15j$$

$$I_s = I_r + I_0 = (12.52\angle -18.04) + (1.15\angle -90) = 12.92\angle -22.9\,A$$

1.4 Calculate stator and rotor inductance in mH

$$I_r = \frac{V_s}{\sqrt{\left(R_s + \frac{R_r}{s}\right)^2 + j\left(X_s + X_r\right)^2}} \quad \Rightarrow \left(X_s + X_r\right) = 5.69\,\Omega$$

$$X_s = X_r = \frac{5.69}{2} = 2.85\Omega \qquad L_s = L_r = \frac{2.85}{2\pi \mathrm{f}} = 9.07 mH$$

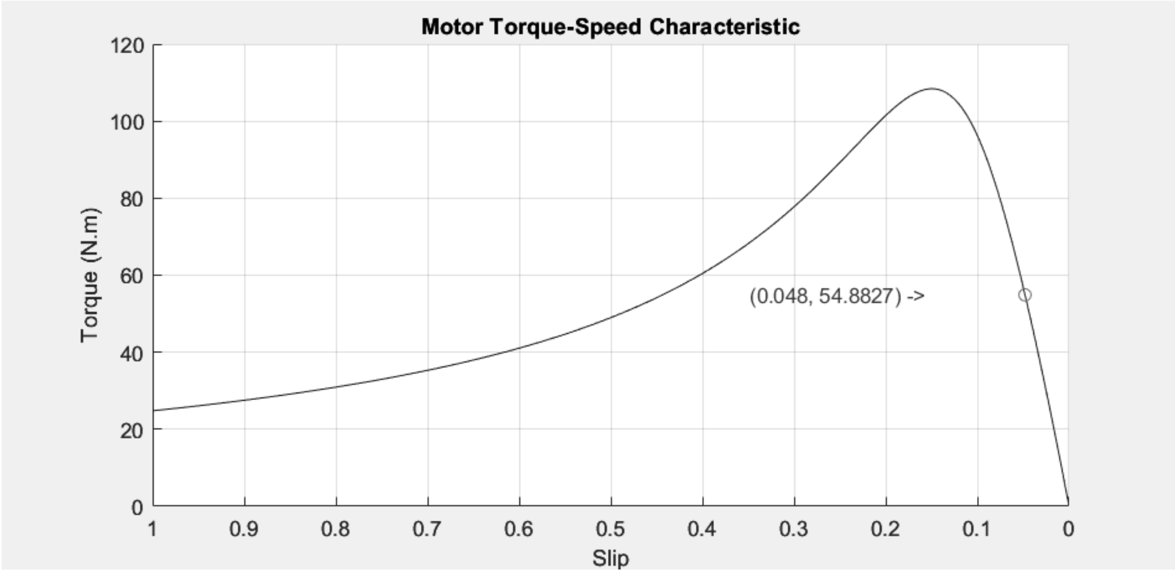
MATLAB Solutions

1.5 Using MATLAB, build an M-code based on the design data to plot the motor torque speed and stator current-speed characteristics in separate graphs for the slip range (0 < s < 1). Show and point in the figure the values of the torque and current at the full load slip. Also, record the starting current.

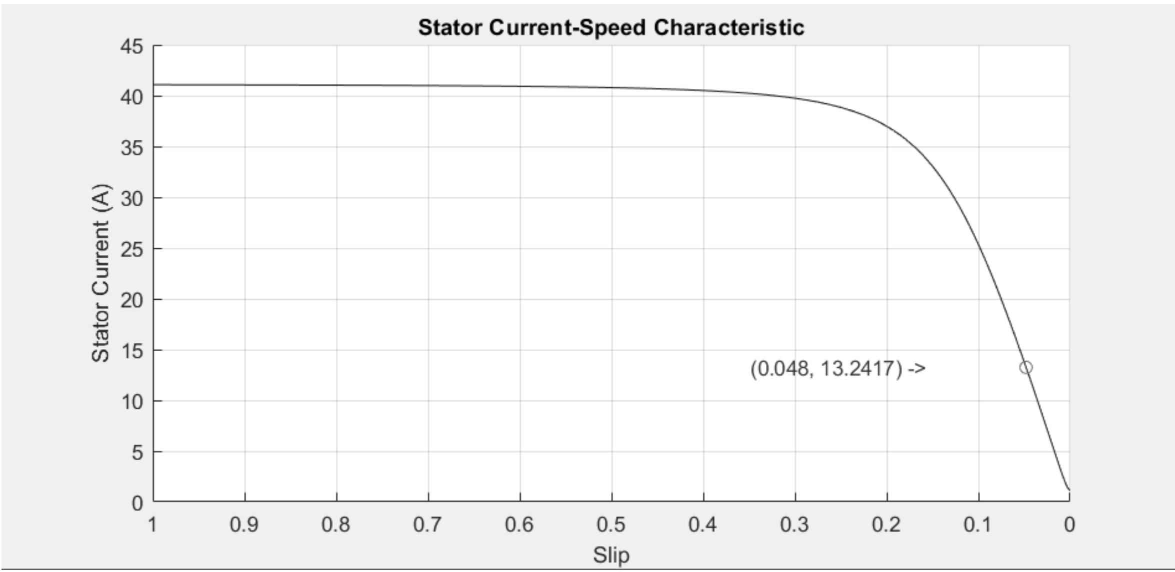
```
% motor parameters
P = 7460; Tfl = 49.89;
Vs = 230; f = 50;
Rs = 0.8; Rr = 0.8;
Is = 12.21; Ir = 12.52; Im = -1.15j;
Xs = 2.85; Xr = 2.85; Xm = 200.12;
Ns = 1500; ws = Ns * (2*pi/60);
s = linspace(1, 0, 1000); sfl = 0.048;

% rotor current
Ir = Vs ./ ( (Rs+(Rr./s)).^2  +  1j*(Xs + Xr)^2 ) .^0.5;

% torque-speed
Td = (3 * Rr * abs(Ir).^2) ./ (s * ws);
Tfl = interp1(s, Td, sfl);

% stator current-speed
Is = abs(Ir + Im);
Isfl = interp1(s, Is, sfl);

% plot torque-speed
figure; hold on; grid on;
plot(s, Td, 'b'); plot(sfl, Tfl, 'o');
text(sfl + 0.3, Tfl, ['(' num2str(sfl) ', ' num2str(Tfl) ') ->'],
'Color','red');
xlabel('Slip'); ylabel('Torque (N.m)');
title('Motor Torque-Speed Characteristic');
set(gca, 'XDir', 'reverse');

% plot stator current-speed
figure; hold on; grid on;
plot(s, Is, 'b'); plot(sfl, Isfl, 'o');
text(sfl + 0.3, Isfl, ['(' num2str(sfl) ', ' num2str(Isfl) ') ->'],
'Color','red');
xlabel('Slip'); ylabel('Stator Current (A)');
title('Stator Current-Speed Characteristic');
set(gca, 'XDir', 'reverse');

% Record starting current
starting_current = Is(1);
disp(['Starting Current: ' num2str(starting_current) ' A']);
```

The above code calculates the rotor current at slips 1-0 and then uses these values to calculate both the torque and the stator current at different slip values. It then interpolates the graph to find the torque and current at full load. After the plots, It returns the starting current to the command window.

MATLAB Solutions Continued



This is the result of the torque-speed calculation. This graph is reversed along the x-axis to accurately represent the motor's behaviour given that the starting slip is 1.



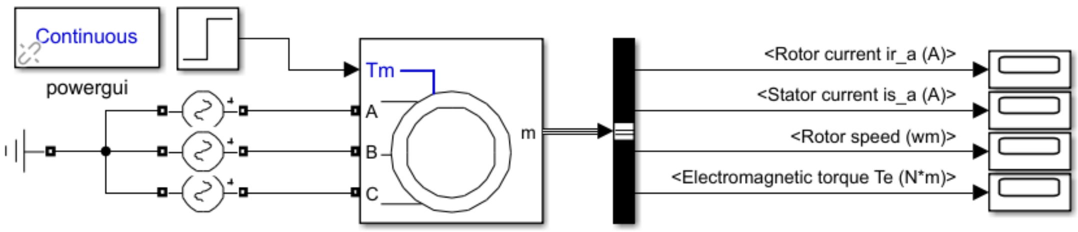
This is the result of the current speed calculation. It shows the stator current through all slip values and behaves as expected.

```
Starting Current: 41.0778 A
```

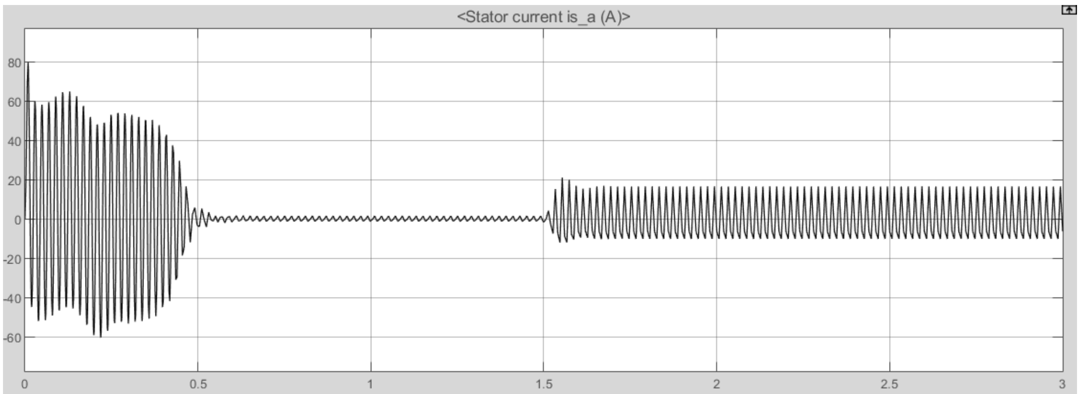
This value was printed to the command window and shows the initial value of the stator current when the slip is equal to 1.

SIMULINK Solutions

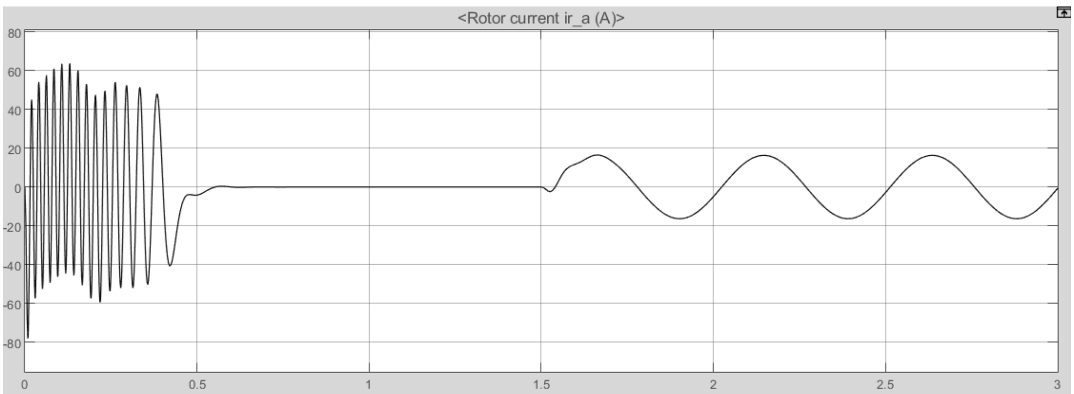
1.6 Build a SIMULINK model that simulates the motor performance at full load using the rated voltage and designed data motor parameters.



This Simulink model utilises a three-phase motor to simulate the desired results. The torque is applied via a step block at 1.5 seconds.

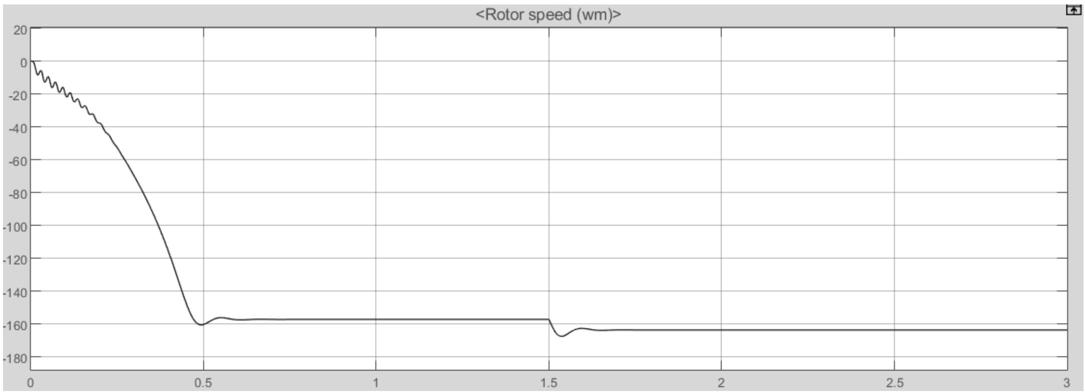


This is the simulated stator current, which has high values initially to overcome the inertia of the motor, then settles at a no-load state. Once torque is applied at 1.5 seconds, the current needs to increase to match the torque requirements.

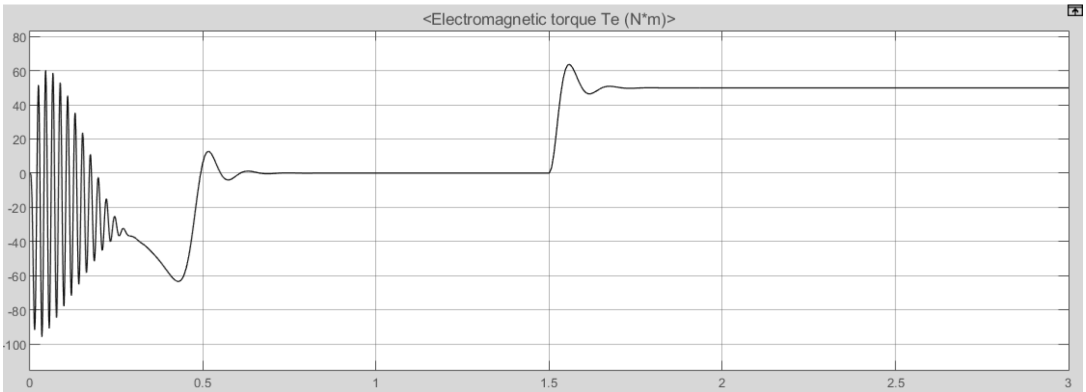


This is the simulated rotor current, which behaves as expected, reacting to the magnetic field generated by the stator. The current increases after 1.5 seconds, as the stator current also increases

SIMULINK Solutions Continued



This shows the rotor speed in angular frequency after the simulation. The speed is negative simply because of how the three-phase supply is connected to the motor. As seen, there are undesirable oscillations initially, leading to vibrations and losses.



The torque is initially high and oscillatory as it overcomes the inertia of the motor. Since the torque is controlled by the step block, it settles at no load before the torque increases, and as expected, transitions to full-load torque after application.

Solution Comparison

1.7 Tabulate the results showing the difference between analytical results, MATLAB code, and SIMULINK at full load and starting. Comment

	Analytical	MATLAB	SIMULINK
I_s starting	38.91 A	41.08 A	~60 A
I_r starting	38.91 A	29.59 A	~50 A
N_r starting	0	0	0
T starting	24.8 Nm	24.8 Nm	~35 Nm

There are some slight differences in the values calculated, this is expected as the analytical solutions assume an ideal machine, whereas the Simulink model is not ideal. The starting currents are higher in practice than in theory because of the high oscillatory behaviour of the starting current. The torque is also very oscillatory when starting, but the average is only slightly higher than the theoretical.

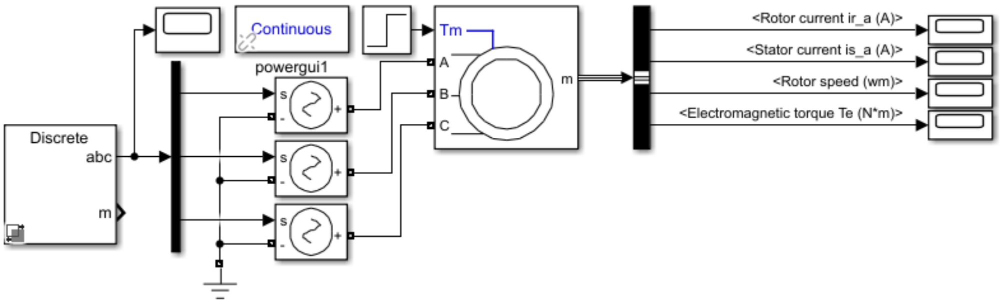
	Analytical	MATLAB	SIMULINK
I_s full load	12.92 A	14.28 A	~13 A
I_r full load	12.52 A	13.11 A	~16 A
N_r full load	1428 rpm	1428 rpm	1576 rpm
T full load	49.89 Nm	49.89 Nm	49.89 Nm

At full load, the currents behave somewhat as expected, with the stator current staying the same, but the rotor current showing a slightly higher value. This could be a result of many effects in Simulink which reduce efficiency. The rotor speed is also higher in Simulink, this could also be a result of inefficiencies leading to more speed required to match the given torque.

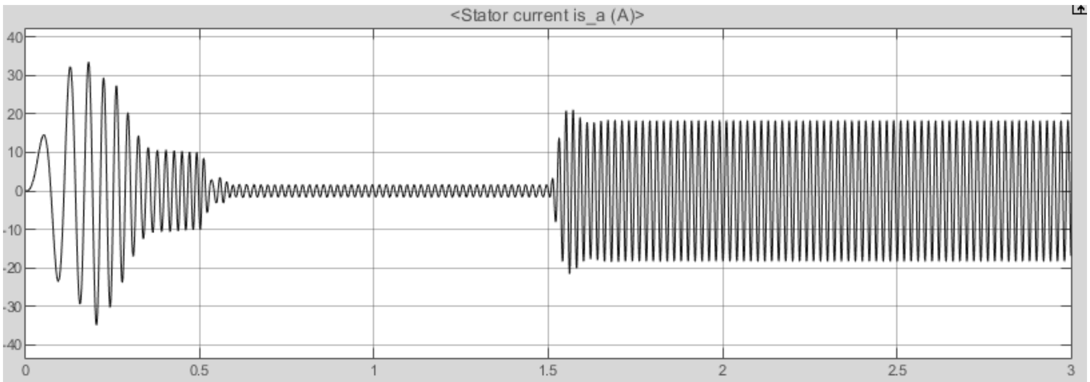
The results from Simulink are also not accurate because of the non-uniform nature of the graphs, leading to inaccurate readings and values (hence the ~ representing an approximate reading). However, as a whole, there are no drastically unexpected results, meaning the motor has been simulated correctly.

Soft Starter Implementation

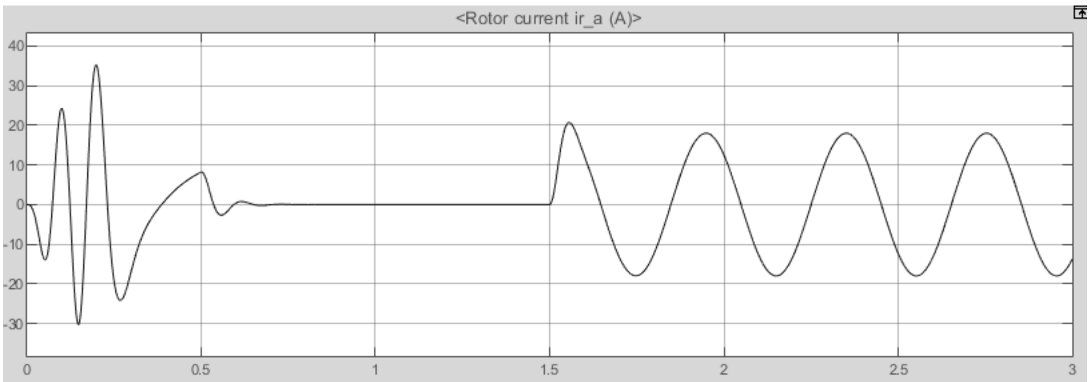
1.8 The motor will be used in a frequent starting mode. Build a soft starter with a V/f scheme using MATLAB/SIMULINK.



The Simulink model above implements a soft starter via a programmable signal generator, outputting three waveforms which control voltage sources, which are input to the motor. The signal generator increases to the desired frequency and voltage over 0.5 seconds.

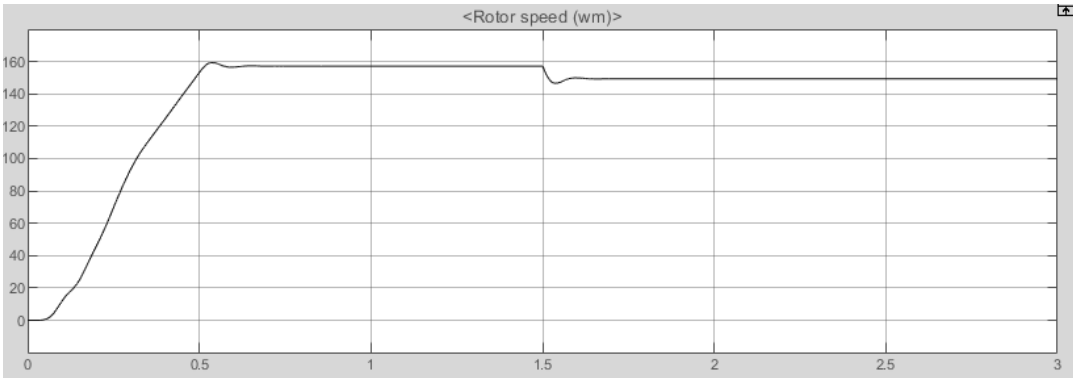


The soft starter results for the stator current drop the starting current significantly from ~60 A to a peak of ~35 A. This is good, as it reduces risk to components, and thermal management becomes easier, as there is less generated heat

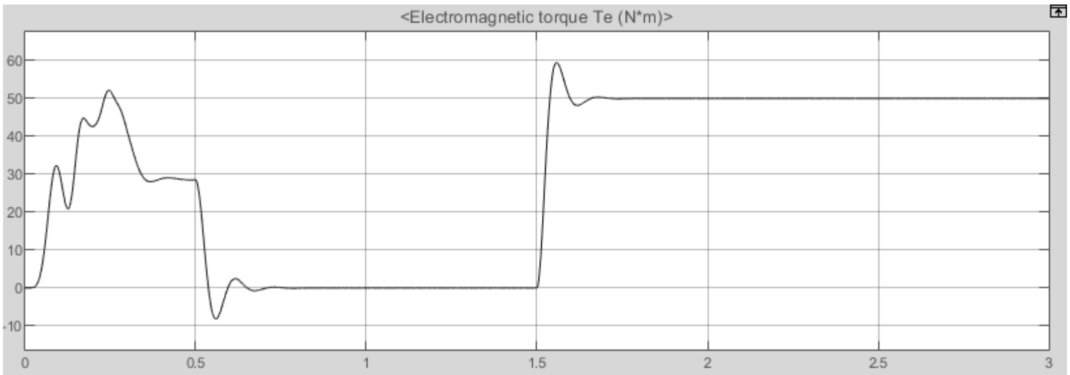


Similar to the regular start, the rotor current follows the stator current, but again, drops from ~50 A to a peak of ~35 A, which also improves the thermal losses.

Soft Starter Implementation Continued



The speed of the soft starter is shown here (also in angular frequency) and shows a steadier speed increase compared to the regular start, where a few fast oscillations were leading to vibrations and losses in the machine.



The torque behaviour improves significantly with a soft starter as well. There are fewer oscillations compared to the regular start, meaning increased control and fewer vibrations and overall efficiency losses in the motor.