University of Utah
Electrical & Computer Engineering Department
ECE 3600 Lab 4

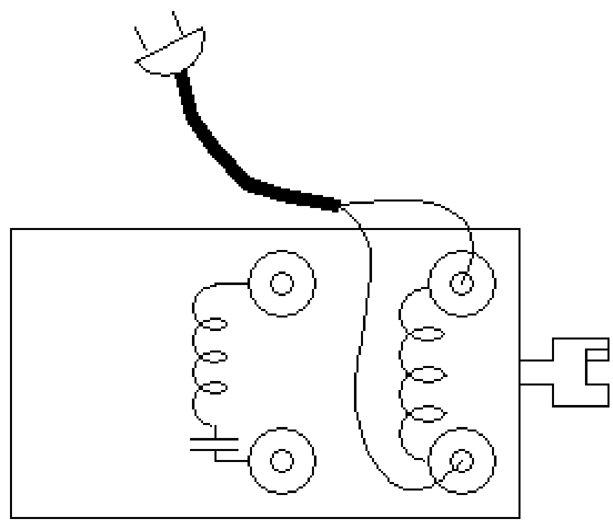
Induction Motor

Objectives

1. Learn about starting the single-phase induction motor.
2. Evaluate the torque-speed characteristics for a small 2-phase induction motor using the dSPACE system. This part of the lab draws directly from one of the labs in ECE 5570, “Torque Curves of Induction Motors”.

Equipment and materials to be checked out from stockroom:

See the last page of this lab and cut out the check-out list. Check out those items your TA says you will need. He may modify this list if he intends to set up a couple of dSPACE systems himself for everyone to use in turn.



Starting the Single-Phase Motor

Mount the blue single-phase induction motor on the motor rack. Connect the power cord to the main winding, as shown. Plug the cord into the power strip and turn it on. Notice that the motor doesn’t turn. This is because one phase can only produce a magnetic field that swings back and forth 60 times per second, but does not rotate. Without a rotating magnetic field, the rotor may hum a bit, but it will not start rotating. Give the motor shaft a spin in either direction to get it started. Now it will continue to rotate because of the nature of the “dual rotating” magnetic fields discussed in class. After the motor spins up to full speed, turn off the power and let it come to a stop. Turn on the power again and manually start the motor in the opposite direction. Notice that it will work equally well in either direction, depending only on how it is started. This is typical of a single-phase induction motor. Turn off the power and let it come to a stop. Describe what you have just done in your lab notebook.

Now connect the second winding (with the capacitor) in parallel with the first and turn on the power. The motor will now spin up on its own. This is because the second winding is positioned at a 90 (actually 90 ÷ number of pole pairs) with respect to the first and the current in the second winding is out of phase with the first. The capacitor in series with the second winding provides the needed phase shift. Note the direction of rotation. If you dare, carefully disconnect the second winding while the motor is running and note that the motor continues to run with no problem. Otherwise refer back to how the motor ran with only one winding before, once started. Turn off the power and let it come to a stop. Describe what you have just done in your lab notebook, noting that the second winding could be used just for starting, if desired.

Swap the connections to one of the windings, turn on the motor and note the direction of rotation. Turn off the power and let it come to a stop. Repeat this until you have tried all four possible connections. Describe what you have just done in your lab notebook and draw some conclusions about connections and starting direction.

The Torque-Speed Curve of an Induction Motor

Note: If you have taken ECE 5570 you may skip this part of the lab by simply showing your TA your 5570 lab notebook and/or report. Don't skip the "Conclude" section. If you don't have any documentation, sorry, you'll have to do it again.

Check with your TA to see if you will be setting up your own dSPACE experiment or if he will let you use one that he has set up.

dSPACE I/O box

Before you turn on the computer, connect the dSPACE I/O box (A rectangular grey box with several BNC ports on it) to the computer via the thick flat cable provided with the box.

Turn on the computer and access the lab website. You should be able to find the Simulink model (.mdl) and dSPACE layout (.lay) files here. If not, please ask the TA to provide you with these files. Download or save these files in a separate folder, say "Lab4" in the C drive of the computer (>>C:\ > Users > your user file), or an external thumb drive. Be sure to never save them in the X drive.

Simulink Model

Open the .mdl file with <u>*Matlab2014a*</u>.This is the Simulink model that will be used for this experiment. Examining this model should reveal sufficient information about its design. The constant blocks "Start", Speed" and Vpk" will be treated as inputs in the real time simulation using the dSPACE Control Desk software.

Building the Simulink model

In order to build the Simulink model, first define the sampling period. In the Matlab Command Window, enter Ts = 1e-4, which will set the sampling period to 100µs or the sampling frequency to 10kHz.
Change the simulation time to infinity from the *Model Configuration Parameters* in the Simulink toolbar: <u>>> Toolbar > Simulation > Configuration Parameter > Solver > Simulation time > Start time / Stop time > 0.0 / inf.</u> Also, change the fixed-step size and solver, under solver option, to 0.0001 [s] and ode1(Euler) respectively.
<u>>>Toolbar > Simulation > Configuration Parameter > Solver > Solver options > Type / Solver > Fixed-step / ode1(Euler) > 0.0001.</u>

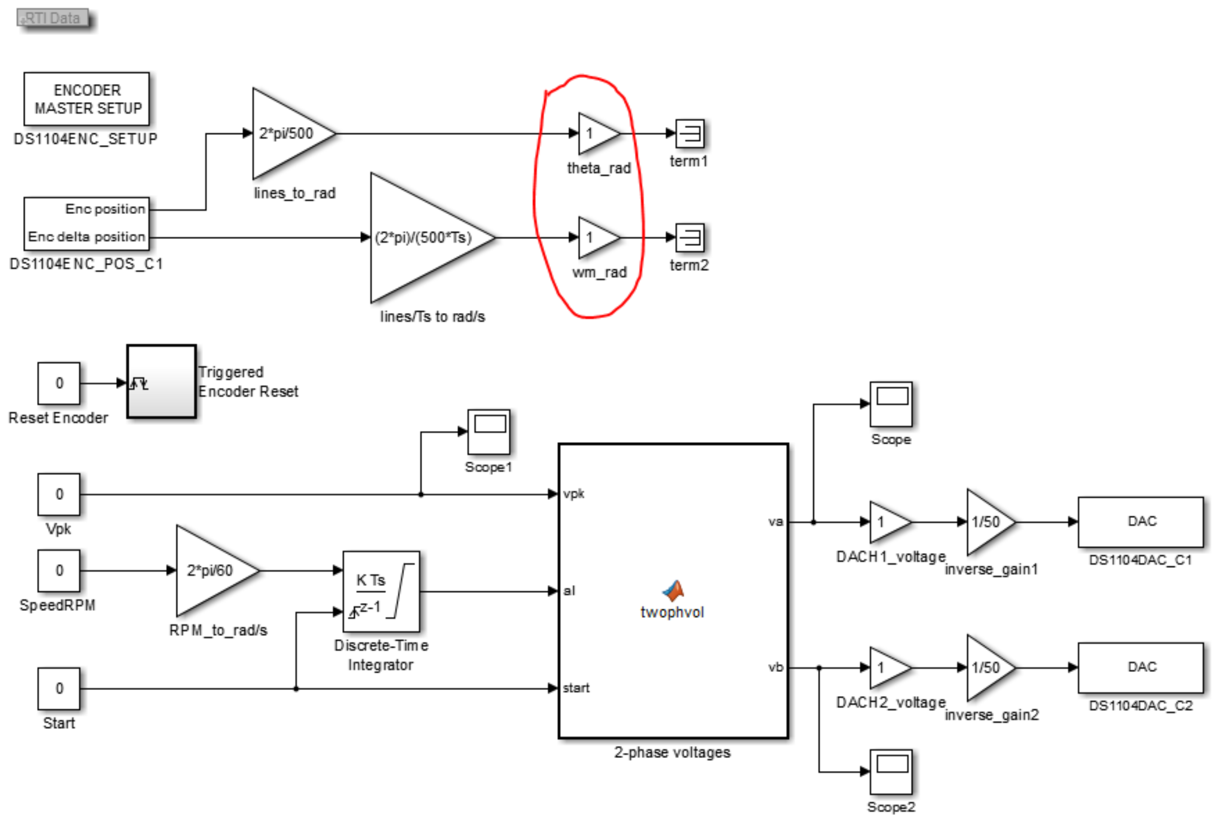


Figure 1: Simulink Model

Ensure that the following settings are also configured in the Model Configuration Parameters.
>> *Data Import/ Export* > Uncheck 'Limit data points to last: (integer)'.
>> *Optimization* > Uncheck 'Block reduction'.
    >>Expand optimization by clicking on the drop down list > *Signals and Parameters* > Uncheck 'Signal storage reuse'.
>> *Code generation* > set 'System target file' to rti1104.tlc by choosing it in the browse options.
>> Expand Code generation by clicking on the dropdown list > *RTI simulation options* > ensure that the 'Initial simulation state' is set to 'STOP'.

Now, in the Matlab command window, type "revertInlineParametersOffToR2013b". Before building this model, ensure that the Matlab directory path is set to the destination folder "Lab4" and then with "Ctrl+B", you can build the model. This will generate a .sdf file in your destination folder if the process completes without any errors. This file is critical for the conception of a dSPACE experiment.

dSPACE Control Desk

Open the dSPACE program by double clicking the "dSPACE ControlDesk 5.2" icon on the desktop or in the start menu.

<u>Create a new project + experiment.</u>
File > New > Project + Experiment.
This will open a new window which will take you through the necessary steps to create a new project + experiment which you will use in the lab experiment.

- Give the project a name and set the location for the root directory (your destination folder).
- Give the experiment a name.
- Check that the "DS1104 R&D Controller Board" is selected.

Open the .sdf system description file through: Import from file… > the folder that the model is saved in (destination folder) > the .sdf file with the same name as the model. Note that only one .sdf file can be open in dSPACE at a time.

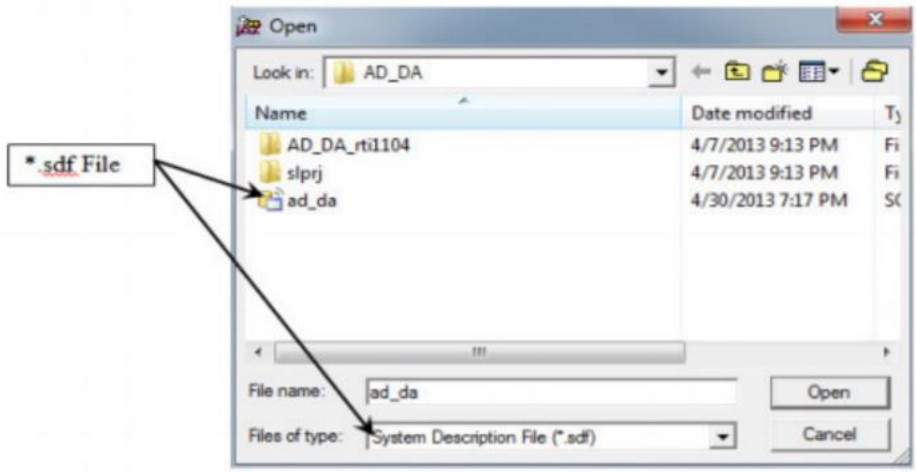


Figure 2: Importing the .sdf file *(For representational purposes only)*

Loading a .sdf file will load all the variables created on Simulink into dSPACE, where a layout is built for interfacing purposes. The variables available through Simulink can be seen in figure 3 and 4. The window in figure 2 shows the .sdf file being selected for loading. On making any changes to the original Simulink model, by clicking on the <u>*>>Project tab* > Right click on .sdf file > *Reload variable description*</u>, you can update variables to their latest values without restarting dSPACE.

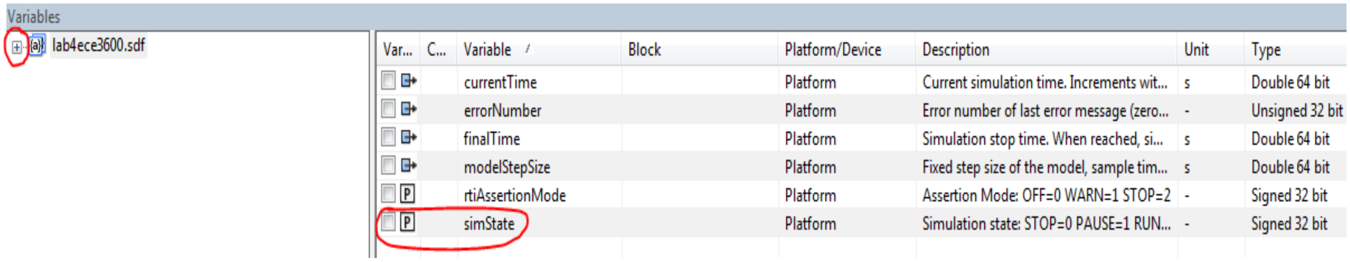


Figure 3: The variables that were loaded onto dSPACE via the .sdf file

A blank layout is automatically opened up on completing the creation of the project+experiment. Close this layout as we will be using the layout that was provided, either on the website, or by the TA. To open the provided layout, >> click on "Layouting" on the toolbar > Import layout > open the .lay file in your destination folder. Examine this layout and the various instruments present. The variables should have already been mapped to these instruments, but if not, here's how to do it:

Note that there is a push button panel with two buttons (ON and OFF) and an indicator LED on the top left corner of the layout. These instruments are to be mapped with the variable *simState*. This can be seen in figure 3, circled in the list of variables. To map it to the instruments, drag and drop the variable onto both the instruments. Once a variable is mapped to an instrument, a red link symbol appears to the left of the variable's name to indicate that it has been mapped, as seen in figure 4.

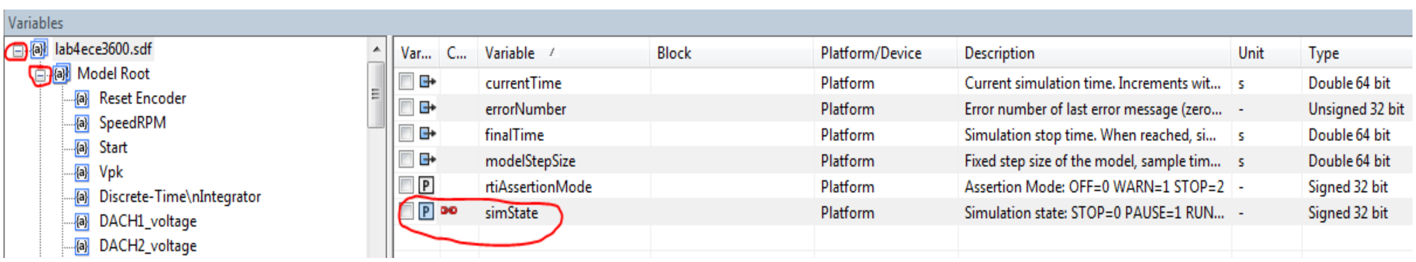


Figure 4: Mapped variable simState

The following can also be noted from figures 3 and 4: The simState and several other general experiment specific variables are found in the variable list by selecting the .sdf file in the "Variables" window; on expanding the .sdf file and then the Model Root under it, the variables that were designed on the Simulink model can be found.
The "Start" variable found under the model root should be mapped to a check box (figure 5). This variable enables the model to provide the proper sine wave outputs on entering the appropriate frequency (in rpm) and peak voltage.

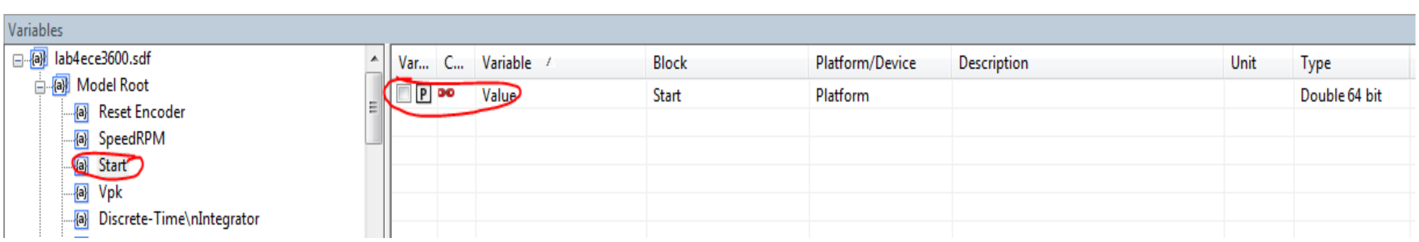


Figure 5: Start variable

Note that on clicking the variable path under the model root, you shall see the variables present in that path on the list on the right.

Similarly, map the variable “Reset Encoder” to the other checkbox. The two blank rectangles under the check boxes are numerical displays. Map the variables “theta_rad” and “wm_rad” to the first and second box respectively. When you open the path to these variables, you will see that there are two variables, “Gain” and “Out1” associated with them. The gain is a constant value “1” that you can see in the Simulink model, where there are gain blocks named as “wm_rad” and “theta_rad” (refer figure 1). The “Out1” variable is the output signal from that block, i.e. the actual variable that gives you the position or speed value. So, make sure to map the “Out1” variables in this case and not the “Gain” variables (figure 6).

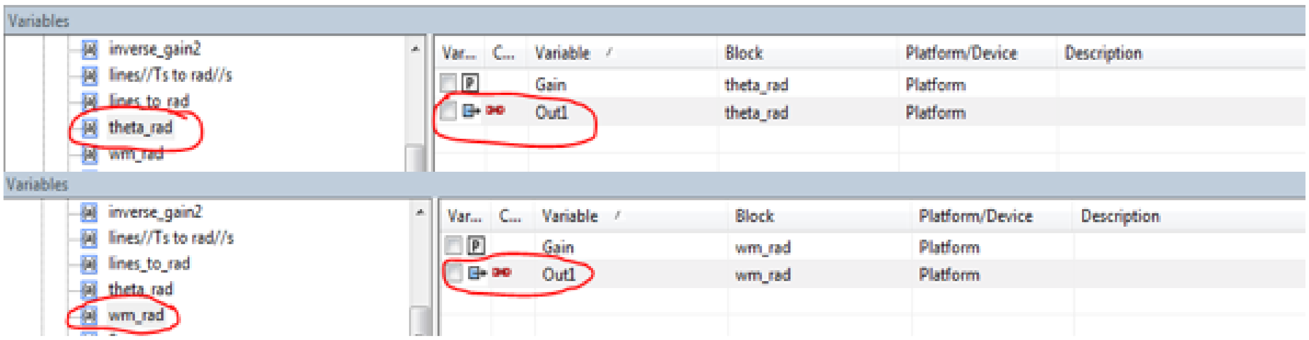


Figure 6: theta_rad and wm_rad

You will need to map theta_rad and wm_rad (Out1) to the plotters as well, to record them in real time. So drag and drop one variable onto the red block in the y-axis of the plotter (one variable per plotter).

The two blocks under the display blocks with increment/decrement buttons are numerical input blocks. Map “Vpk” to one block and “SpeedRPM” to the other. The overall layout should now look as shown in figure 7.

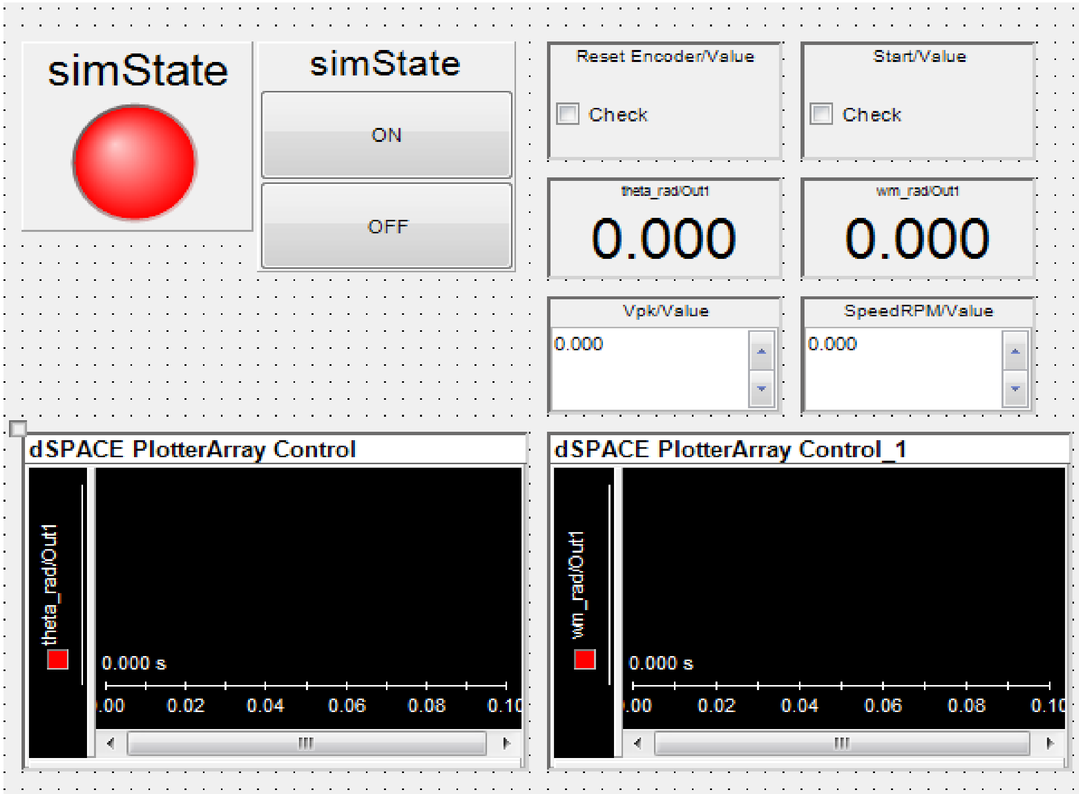


Figure 7: Overall layout

Hardware

Set up the 2-phase induction motor, coupled to the stand alone encoder (encoder in a bracket) on the metal rack by bolting them down on it. Using the D-D encoder cable provided, connect the encoder port on the standalone encoder to the incremental encoder channel one "Inc1" on the dSPACE I/O box. We will be powering the motor through the dual power amplifier. Connect the dual power amplifier to a power source. The BNC ports on the amplifier are the inputs and the corresponding set of banana ports on the other side of the amplifier box are the outputs. DACH 1 and 2 channels are set to output phases A and B respectively. So, connect DACH channels 1 and 2 to the amplifier via BNC cables. For now, we shall leave the connections at this stage, where the amplifier is fed with inputs and is powered, to test the outputs of the amplifier.

dSPACE

Now, on dSPACE, click on the "Go Online" button (on the toolbar) to activate the layout, then click on the "Start Measuring" button to initialize the plotters. Then, push the ON button in the simState block; when the indicator light is green, it implies that the Simulink program is now active. The matlab code that was written for the generation of waveforms however, is programmed to start only when the "Start" check box is checked. So check the "Start" check box. Enter a value for the speedRPM, say 1800. You may simply type this value in. Also, enter a 10V value for the Vpk variable. This should give you a sinusoidal waveform with a peak value of 10 volts and at a 30Hz frequency at the amplifier output terminals (red and black banana plugs) when it is ON. So, with the amplifier ON, use a multimeter to measure the voltage at both outputs. You should see a 10 V output. Considering that the encoder cable was plugged in, manually rotating the shaft of the motor should allow you to see the change in position on the layout. Bring the voltage and speed values down to 0, uncheck the “Start” check box, push the “OFF” button on the simState block to see the indicator go red and then, click on the “Go Offline” button to disengage the layout. You will always need to follow this procedure and the one mentioned earlier in this section to end and begin the dSPACE experiment respectively.

Hardware

With the experiment and all the power sources OFF, connect the output of the amplifier to the induction motor via banana cables. The convention is to assume that the red knob on the induction motor corresponds to phase A and the black one corresponds to phase B. Please note that the two windings of the induction motor are connected together. Although there are four banana plugs on the motor frame, the two middle plugs (colored blue) are connected to the same wire. The two ground plugs of the amplifier are also connected together. Therefore, make sure that the grounds of both amplifiers (black outputs of the amplifiers) are connected to the blue plugs of the motor frame. Also, if the direction of rotation is negative in your initial experiments, swap the phases, so that the direction of rotation changes.

dSPACE

On dSPACE, while offline, click on the “Measurement Configurations” tab that you can see to the left of the main window (figure 8-left). Click on the recorder to see the recorder buttons. You will need to adjust the properties of the recorder to automatically export a .mat file to your destination file. Right click on the recorder and select “Instrument Properties”. The relevant section on the properties window can be seen in figure 8. Expand “Storage Information”, check the “Automatic export” option, set the name prefix of the data files as desired, select the folder into which you want the data files to be sent (your destination folder) and check the “Automatic save dialog” option if you want to be prompted to save or discard your data. Save the experiment after you make these settings. Now you are set to conduct the experiment.

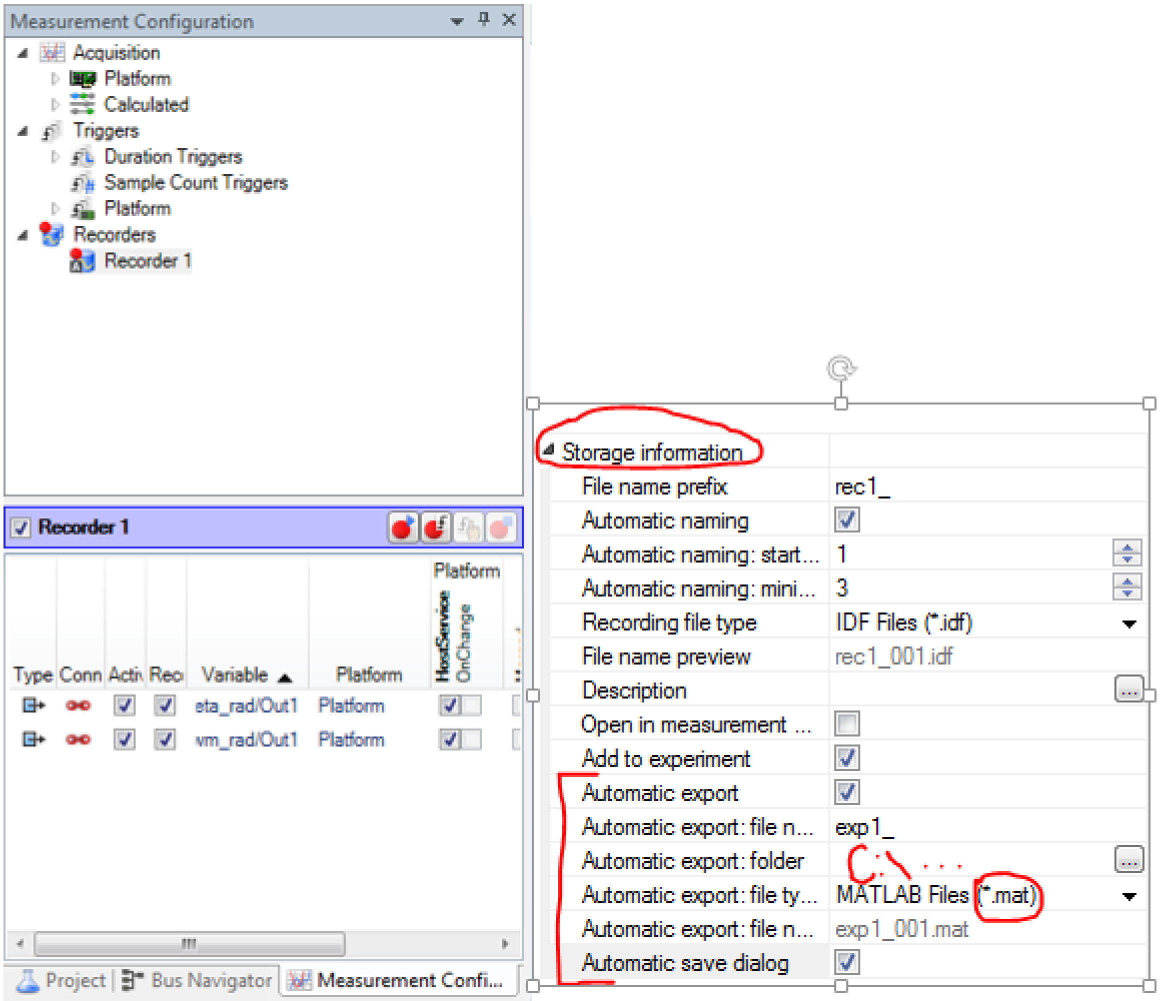


Figure 8: The Measurement Configuration widow when clicked on the tab in the bottom (left); Recorder properties settings (right)

Turn the power to the amplifier and experiment back on (Go online and push ON button). Enter 3600 for the SpeedRPM value (corresponds to 60 Hz) and 24 V for Vpk. Push the “Start immediate recording” on the recorder and then check the “Start” button. The motor will only rotate once the start button is checked. Push the stop recording button at the approximate 10 or 5s mark, when the motor has reached steady state speed. This is the response of the motor for sinusoidal voltages with a peak value of 24V and a synchronous speed of 3,600 rpm. Reduce the Vpk and SpeedRPM to 0, uncheck the “Start” button, push the OFF button and go offline. Determine the value of the speed in steady-state (it is useful to average the velocity over some period of time after it has stabilized). Calculate the values of the slip (in rad/s) and of the normalized slip (in %).

Measuring the torque curves precisely would require a torque sensor. However, useful results can be obtained from the acceleration of the motor alone. The torque itself is not obtained. Rather, the torque divided by the inertia J is obtained, but that is all that is needed for control system design.

The acceleration of the motor can be reconstructed using numerical differentiation. For this purpose, it is necessary to filter the velocity. One has that

$$\frac{d\omega}{dt} = \frac{\tau_e(\omega,\omega_e)}{J} - \frac{\tau_{LF}}{J} \tag{1}$$

assuming that the electromagnetic torque can be approximated by the steady-state value. Further assuming that the load torque is constant (it consists mostly of Coulomb friction in the set-up), the total torque, $\tau_e(\omega,\omega_e)-\tau_{LF}$, divided by the inertia J, is equal to the angular acceleration.

Apply a Butterworth filter and differentiate your captured data using, for example, the code below

```
[b,a] =butter(3,0.01); % 0.01 is the cutoff frequency divided by half the sampling frequency
speed_filt = filtfilt(b,a,inc_vel)
dw = [0 diff(speed_filt)]/Ts;
```

where Ts=1e-4 is the sampling period.
Plot the following in subplots:

- Velocity ω *vs.* time
- Acceleration ($d\omega/dt$) *vs.* time
- Slip ($\omega_e-\omega$) *vs.* time
- Acceleration ($d\omega/dt$) *vs.* slip ($\omega_e-\omega$)

Tabulate your values for speed, slip, normalized slip, and k for the three speeds.

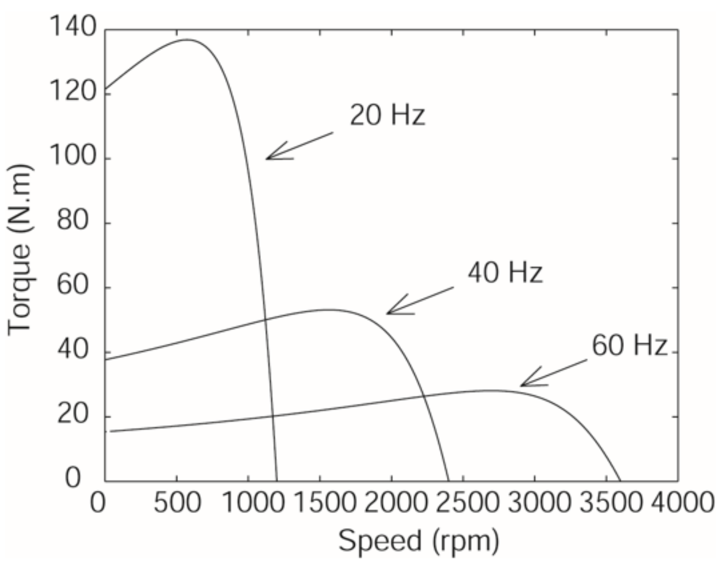


Figure 9: Torque curves of an induction motor

Use the filtered velocity and acceleration for your plots. Produce another plot that shows all three acceleration *vs.* slip curves in a single figure to compare with Fig. 9. For small slip and $n_P=1$, one has that

$$\frac{\tau e}{J} = k(\omega_e-\omega) \tag{2}$$

where

$$k = \frac{M^2}{JR_R} \frac{V_S^2}{\left(R_S\right)^2 + \left(L_S \omega_e\right)^2} \quad (3)$$

On the other hand

$$\frac{\tau_{LF}}{J} = k\left(\omega_e - \omega_{SS}\right), \quad (4)$$

where ω_{SS} is the steady-state speed. From the plot of acceleration *vs.* slip, find the value of the constant k such that the best fit is obtained for

$$\frac{d\omega}{dt} = k\left(\left(\omega_e - \omega\right) - \left(\omega_e - \omega_{SS}\right)\right), \quad (5)$$

In other words, *k* is the slope of the line relating $d\omega/dt$ to $(\omega_e - \omega)$ close to ω_{SS}.

In order to find *k, p*erform a linear fit in Matlab (using the function *polyfit*) over the linear region (close to ω_{SS}) of each data segment. The estimate of k will be very approximate, but only an approximate number is needed for control design.

Repeat the estimation of the parameter k at synchronous speeds of 1,200 and 2,400 rpm. Report values of the steady-state slip and *k* for each speed. Equation (3) predicts that the constant k is inversely proportional to $1 + (L_S / R_S)^2 \cdot (\omega_e)^2$. From this fact, and from your measurements, determine a ball park estimate of the constant L_S / R_S Produce a set of 4 plots as before for each of these three speeds.

Note: Be sure to turn off the experiment and the power to the amplifier when not in use. The amplifier tends to heat up when left on for too long. Also take proper measures as described above while activating and deactivating the experiment.

Check off, Conclude and Clean Up

Check off and conclude as always. Be sure to compare what you found in the lab to what you saw in your text and in class. Guess the class (A,B,C,or D) of this motor from the shape of its torque-speed curve.

Note: To unpack an .mat file that has been exported to your destination file, you will need the Mat_Unpack.m file. Download this from the website into your destination folder (it is critical that this file is present where the data files are). With the Matlab directory path set to your destination folder, type “Mat_Unpack” in the command window, when prompted, enter the name of the data file without the .mat extension. Name all the variables that are listed. Then you may use these variables to generate plots or manipulate them to calculate the required derived variables and plots.

If the TA set up the dSPACE stations for you, please offer to help clean up before leaving.

NAME	
DATE	
CLASS	ECE 3600 SECTION 001
QUANTITY	DESCRIPTION
1	Power wire kit
1	Power strip
1	“Suicide” cord
1	Single-phase induction motor (blue)
1	2-Phase induction motor
1	Encoder in a bracket
1	Dual power amplifier
1	dSPACE kit with encoder cable and I/O breakout box
1	Motor rack
1	BOB (bucket of bolts)