

# EE3501, Experiment 10

## Motor Drives

Jonathan Kimball, April 23, 2025

### Abstract

This experiment explores motor drives, variously called “adjustable speed drives,” “variable frequency drives,” “servo amplifiers,” and combinations thereof. The drives we have are versatile and may be used on both induction motors and “servo” motors (actually permanent magnet synchronous machines). They also support a variety of control methods, ranging from open-loop to high-performance closed-loop. There are many acronyms in common use in the industry; consult Table 1. Please note that the first several pages of this document are intended to provide technical background to supplement available textbooks.

## 1 Introduction

Traditional machine analysis assumes steady-state operation. However, since the advent of power electronics (dating to the 1960’s with the invention of the SCR), variable speed applications have become much more important. With the invention of the IGBT in the 1980’s, adjustable speed drives for induction motors and permanent magnet synchronous machines became economical. This document is intended to provide an overview of the concepts related to variable speed operation of motors. For further information, students should consider taking EE5500 and EE6500.

For many years, from the invention of the SCR until the commercialization of IGBTs, soft starts were the only technology available to regulate the speed of an IM. They are still

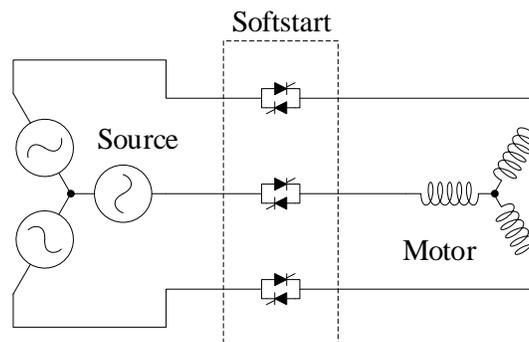


Figure 1: Schematic of a softstart.

Table 1: Common Acronyms in the Motor Drive Industry

Acronym	Meaning
ASD	adjustable speed drive
BJT	bipolar junction transistor
BLDC	brushless dc
DTC	direct torque control
IFOC	indirect field oriented control
IGBT	insulated gate bipolar transistor
IM	induction motor (or machine)
MOSFET	metal-oxide-semiconductor field effect transistor
PMSM	permanent magnet synchronous machine (or motor)
PWM	pulsewidth modulation
SCR	silicon controlled rectifier
VFD	variable frequency drive

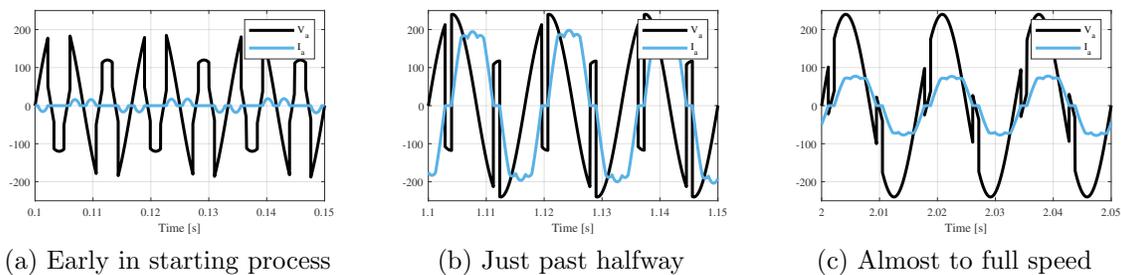


Figure 2: Example waveforms in a softstart.

in common use for starting purposes, and scale up well to high power and high voltage. The circuit topology is shown in Fig. 1.

An SCR is like a diode that can be turned on at an arbitrary time, but turns off when current goes to zero. SCRs are typically used in phase control mode. That is, the phase angle of the voltage at turn-on may be varied. The typical resulting waveform is shown in Fig. 2. Phase control introduces substantial harmonics, but those are not of interest here. The fundamental frequency does not change (so 60 Hz in gives 60 Hz out). By varying the phase delay, though, the RMS voltage may be adjusted. Fig. 3 shows a family of torque-speed curves for a typical IM with varying voltage magnitude, constant frequency.

Generally, this device is termed a *softstart* because that is its purpose: to soften the starting transient. By slowly ramping up the voltage magnitude, the current magnitude also increases slowly, and the speed of the motor increases slowly. This reduces stress on the power distribution network and on the mechanical components that comprise the load. After starting, the SCRs are usually shorted out with a contactor (mechanical switch).

To truly vary the speed requires varying the frequency. Recall that IMs are only efficient in the low-slip regime, that is, just below the synchronous speed

$$n_s = \frac{120f_e}{\text{poles}}, \quad (1)$$

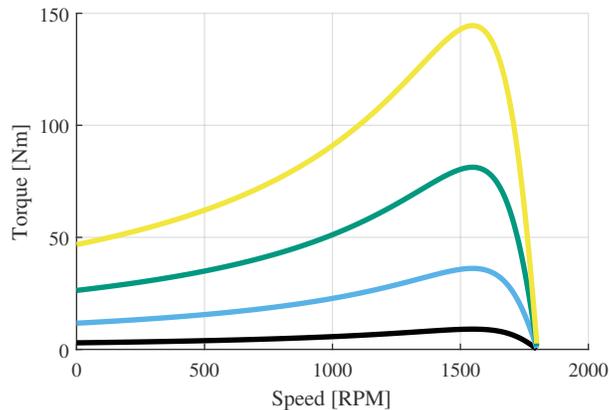


Figure 3: Induction machine torque-speed curves with varying voltage magnitude, as achieved with a softstart.

where  $f_e$  is the electrical frequency. Varying  $f_e$  became possible with the commercial availability of IGBTs. An IGBT is a type of semiconductor switch that resembles a cascode connection of a BJT and a MOSFET. For a time, large BJTs were used for the same function, but were too expensive because of base drive challenges. The current gain of a large BJT might be as low as 10, so huge base drive current sources are required. MOSFETs were and are used for low-voltage applications (such as servomotors, described below), but their losses scale with the square of rated voltage. For industrial applications at voltages from 208 V to 4160 V, IGBTs provide the best cost-performance. They have the gate drive requirements of a MOSFET—relatively easy—and the conduction vs. breakdown voltage characteristics of a BJT—relatively cheap to make a high-current, high-voltage device. The “sweet spot” for IGBT technology is 1200 V breakdown, which is appropriate for a 480 V three-phase system. IGBT ratings are available from 600 V to 6.5 kV.

The basic concept used in a VFD is to vary the voltage magnitude and frequency to vary the motor speed. Fig. 4 shows a family of torque-speed curves for varying frequency. Now, we must distinguish between various frequencies, summarized in Table 2. To maintain constant air-gap flux density, the voltage magnitude  $V_{LL,rms}$  must be varied along with frequency  $f_{out}$ , usually something like

$$V_{LL,rms} = \min \left( V_{boost} + \frac{V_{rated} - V_{boost}}{f_{rated}} f_{out}, V_{rated} \right) \quad (2)$$

where  $V_{rated}$  and  $f_{rated}$  are the nameplate ratings of the motor and  $V_{boost}$  is an extra voltage added to overcome motor and cable resistances at low frequency. Typically,  $V_{boost}$  is around 5-10% of  $V_{rated}$ . The min function clamps the output voltage at the machine rating. Below rated (also called “base”) speed/frequency, the machine operates in constant torque mode—that is, the motor can produce torque equal to its rating at any speed below base speed. Above base speed, the voltage is too low to produce rated flux, so the motor enters “field weakening” and its capability follows a curve of constant power. Also notice that the torque-speed curve extends above the synchronous speed. This regime is called “regen” (short for regeneration) and can be used to slow down the machine. The energy goes into the bus capacitors. It must be bled off, typically through braking resistors.

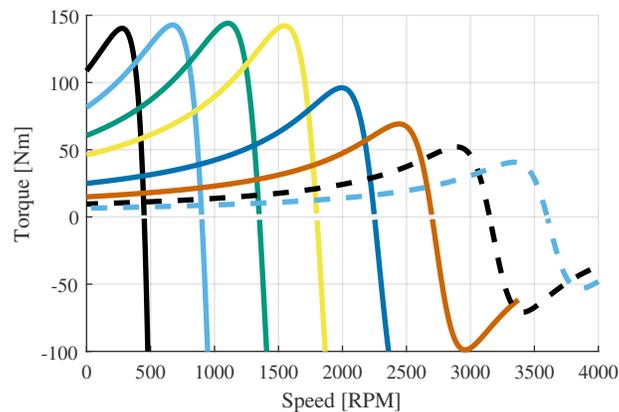


Figure 4: Induction machine torque-speed curves with varying voltage magnitude AND frequency, as achieved with a VFD. Includes regen operation.

Table 2: Important Frequencies in a VFD

Symbol	Meaning
$f_{in}$	Grid frequency; input to VFD
$f_{out}$	Motor frequency; output of VFD
$f_{sw}$	PWM switching frequency

The key concept that makes this work is **PWM**. Fig. 5 shows a typical circuit topology for a VFD. Incoming three-phase power is rectified to provide a relatively constant dc bus voltage. Then the IGBTs are switched on and off to produce a square wave at the output. By varying the duty ratio of the square wave, the moving average voltage may be varied, called *pulsewidth modulation*. Fig. 6 shows a PWM waveform with an unusually low switching frequency. Higher switching frequency corresponds to better sinusoidal output. The motor acts like a low-pass filter so that the currents are nearly sinusoidal. PWM waveforms are normally created by comparing a modulating function (sinusoid at  $f_{out}$ ) to a sawtooth function (at  $f_{sw}$ ).

A typical industrial application requires 50 Hz or 60 Hz nominal output frequency. Most VFDs have a minimum switching frequency of 2 kHz. Some have a default switching frequency higher than this (for example, our VFDs default to 8 kHz), and all have a maximum switching frequency that is significantly higher. Energy is lost each time an IGBT switches, though, so higher switching frequency means lower efficiency and more losses. The choice of switching frequency is a trade-off between audible noise, waveform fidelity, efficiency, and

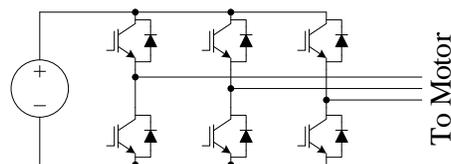


Figure 5: Typical VFD circuit. The dc source shown is typically the output of a rectifier.

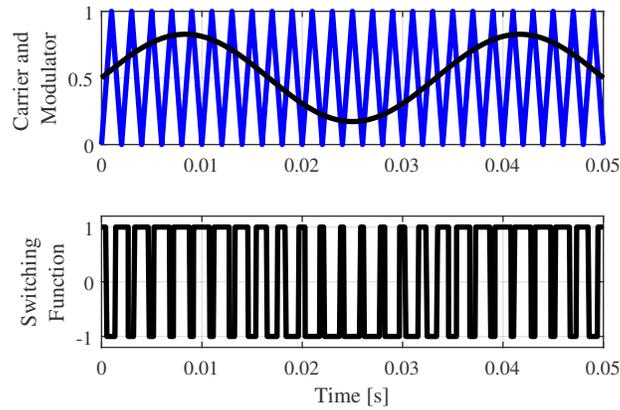


Figure 6: Example PWM process, with a very low carrier frequency to exaggerate.

maximum power capability.

The PWM process takes as an input a desired voltage magnitude and frequency and provides as outputs six switching waveforms. Actually, the outputs are three pairs of switching waveforms: in each IGBT leg, only one IGBT may be on at a time. If the duty ratio of the upper IGBT is  $d$ , then the duty ratio of the lower IGBT is  $(1 - d)$ . (There is also deadtime, but that is a topic for a different course). Suppose the dc bus voltage is  $V_{bus}$  and we would like to create three-phase waveforms with magnitude  $V_{LL,rms,out}$  and frequency  $f_{out}$ . Then the duty ratio for a given leg may be found from:

$$M = \frac{V_{LL,rms,out}}{V_{bus}} \times 2\sqrt{\frac{2}{3}} \quad (3)$$

$$m(t) = M \cos \theta - kM \cos 3\theta \quad (4)$$

$$\theta = 2\pi f_{out}t + \phi, \quad \phi \in \left\{ 0, \frac{2\pi}{3}, -\frac{2\pi}{3} \right\} \quad (5)$$

$$d(t) = \frac{1}{2}(1 + m(t)) \quad (6)$$

$$V_{LL,rms,out} = \frac{MV_{bus}}{2} \sqrt{\frac{3}{2}} \approx 0.6124MV_{bus} \quad (7)$$

$M$  is the *modulation depth*, and  $m(t)$  is the modulating function or waveform that is compared to a triangle wave ranging  $\pm 1$ . For linearity, then,  $m(t) \in [-1, 1]$ . This would imply  $M \in [0, 1]$ .

Unfortunately, this would provide too limited a range of output voltage. For a given source voltage  $V_{LL,rms,in}$ , typically,  $V_{bus} = 1.35V_{LL,rms,in}$ . (For more information, take EE5520.) If we constrain  $M \leq 1$ , then we would constrain  $V_{LL,rms,out} \leq 0.827V_{LL,rms,in}$ . Fortunately, there is a solution. In a balanced wye-connected system, third-harmonic currents cannot flow. So we add the third-harmonic indicated. If we set  $k = 1/6$ , then we can allow  $M \in [0, 1.15]$  and still achieve  $m(t) \in [-1, 1]$ . See Fig. 7 for a graphical example. The three choices for  $\phi$  correspond to the three phases (a, b, c).

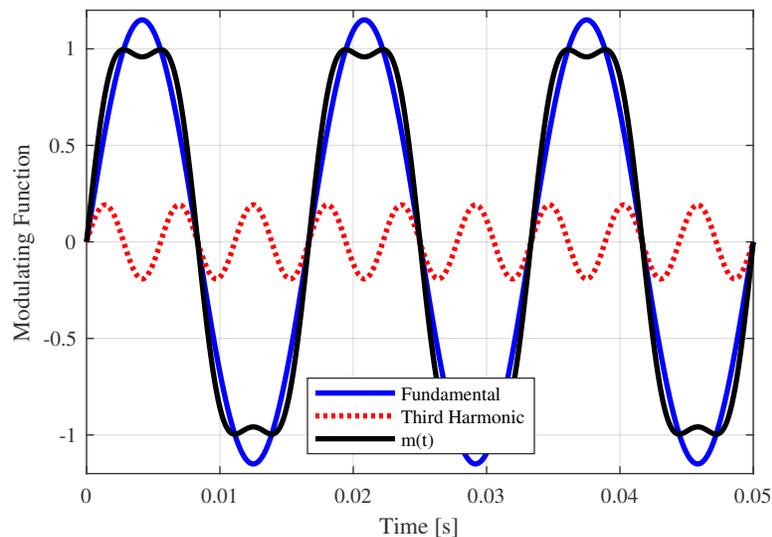


Figure 7: Graphical construction of modulating function  $m(t)$  from a fundamental and third harmonic, to achieve larger than unity gain.

## Control Methods

There are three classes of VFDs. The simplest are called “scalar” or “V/Hz” (read “volts-per-hertz”) drives. Scalar drives only do what has been described above: variable voltage magnitude and frequency, with a quasi-steady-state assumption. That is, speed is only varied slowly. This is totally adequate for most applications, especially fans and pumps. Historically, these were the cheapest type. Slightly better speed regulation may be achieved with *slip compensation*, in which  $f_{out}$  is increased when the load increases.

The second class is called “vector” or sometimes “closed-loop vector.” In this class, output currents are measured and transformed into a current vector (in a  $dq$  reference frame). With the application of fairly advanced control theory, the dynamic performance of the motor can be controlled extremely well. The original vector formulation is indirect field oriented control (IFOC). The main drawback is that speed feedback is required. Somehow, the controller must know the speed of the motor. The common solution is an encoder, which is an optomechanical device mounted on the motor shaft. The added cost of the encoder, along with the wiring and reliability issues, discourages many users from choosing this approach. Also, historically, the drives themselves were significantly more expensive than scalar drives. However, in the past fifteen years or so, the cost difference in the VFD itself has fallen, since most drive manufacturers find it easier to change only software and use the same hardware (same current sensors, etc.) for both scalar and vector drives.

The third class is called “encoderless vector” or “sensorless vector.” This is a compromise solution that first hit the market in the late 1990’s and is now commonly available. There are many flavors; the first truly successful control method is called “direct torque control.” DTC takes two or three steps away from IFOC. Other encoderless vector methods essentially use the IFOC formulation with various observers added. Regardless, the goal is to achieve performance similar to a closed-loop vector drive, which uses an encoder, but without needing

the speed/position feedback. Obviously, truly matching performance is impossible, but a good encoderless vector drive with proper tuning will perform adequately over a broad range of speed and torque. The biggest challenge is achieving good performance near zero speed.

## Servos, PMSMs, BLDC Motors

The above discussion assumes the use of an IM. The same power electronics can be used for a PMSM, just with different control.

A servomotor is defined as a motor that uses feedback to achieve precise positioning. Applications include industrial processes, robots, and other mechanical systems that need to be controlled. For many years, the best solution was a dc motor (usually permanent magnet dc, sometimes separately excited). The advent of VFDs opened up the possibility of using a PMSM, and dramatic cost reductions in rare-earth magnets (especially NdFeB) enabled larger and cheaper PMSMs for a broad range of applications.

In a lot of ways, a PMSM is like a wound-field synchronous machine, except that there is no field current to control. Therefore, the generated voltage is a fixed function of frequency. As in a VFD for an IM, speed is controlled by varying the frequency. Unlike an IM, though, the frequency and speed are exactly coupled—there is no slip. Therefore, some sort of position feedback is essential. The rotating magnetic field on the stator must be synchronized with, and maintain a known angular relationship to, the rotor.

For servos, the typical solution is to use a high-quality encoder, often with Hall tracks. Hall effect sensors provide an output related to a dc magnetic field, and were once used to measure the rotor field as it rotated past the stator. Nowadays, we more typically have an optomechanical device that is aligned with the rotor field to provide the same information. The Hall track outputs are square waves that are synchronized to the three phase line-to-neutral voltages. Servos additionally have more precise encoders (providing perhaps 1000 pulses per revolution) to enable position control.

The control of a “servo amplifier” is essentially the same as a VFD, with the added requirement for synchronism. Most modern servo amplifiers create sinusoidal outputs. The main difference is in software. Whereas a VFD must have frequency actuation and may have speed feedback, a servo must have both plus position control plus some sort of application software to create the position trajectory. In a complex system, the position trajectory is created by a motion controller. The software can become quite involved.

In other applications, this level of precision and complexity is not required. For example, PMSMs can be used as speed actuators instead of torque or position actuators. In that case, the VFD-type hardware is essentially the same but the software can be much simpler, and the encoder can be simpler. Alternatively, there are software approaches that are slightly more complex but eliminate the need for an encoder.

In even simpler applications, sinusoidal excitation is not needed—square wave excitation is acceptable. The control becomes easier, as the IGBT or MOSFET commands are logically related to the Hall tracks. Small “muffin” fans work this way. There are even reduced-switch-count topologies that only require half as many IGBTs or MOSFETs. When used in this way, the PMSM is called “brushless dc” (BLDC) because its overall characteristics resemble a permanent magnet dc motor.

## Nidec Digitax HD M751 Series

The drives used in the laboratory operate in all of these modes with slightly different terminology:

- OL: open-loop mode for IM; open-loop vector has dynamic boost, fixed V/F has fixed boost and linear voltage vs. frequency, quadratic V/F has fixed boost and quadratic voltage vs. frequency for improved efficiency
- RFC-A: rotor flux control for asynchronous motors, that is, vector control for an IM; with or without position feedback
- RFC-S: rotor flux control for synchronous motors, that is, vector control for a PMSM; with or without position feedback

In this set of experiments, we will be using OL (fixed, with and without slip compensation), RFC-A (sensorless), and RFC-S (with feedback) modes.

## 2 Laboratory Software

This set of experiments uses a lot of the equipment:

- Nidec VFD: used for the active motor, either induction or servo. Parameters must be changed for the different operating modes. You will then give a frequency or speed command.
- Yokogawa: used between the VFD and the active motor. You must **activate the line filter and frequency filter** to deal with the PWM. Put in 3P3W mode. When you record data, include voltage, current, active power, reactive power, and frequency.
- Two Flukes for the dc machine. The field will be controlled by the variable dc, connected through Fluke #1 to measure dc voltage and current. The armature will be connected to the load box through Fluke #2, set to measure dc voltage and current.
- The oscilloscope, with one differential voltage probe (P5205) and one current probe (A6302 plus amplifier). The initial scope settings are: current probe on channel 1, differential voltage probe on channel 2, trigger on rising edge of channel 1 (current), horizontal 10 ms/div, **acquire 2M points**.

## 3 Laboratory Experiment

### 3.1 Week 1: Induction Motor

Connect as in Fig. 8. NOTE: Be sure to connect the P5205 to the “sense” terminals at the VFD, and NOT at the motor end of the cable. Set the load box as shown in Fig. 9. **Turn on the fan on the load box.** Make all of the connections while the VFD and variable dc

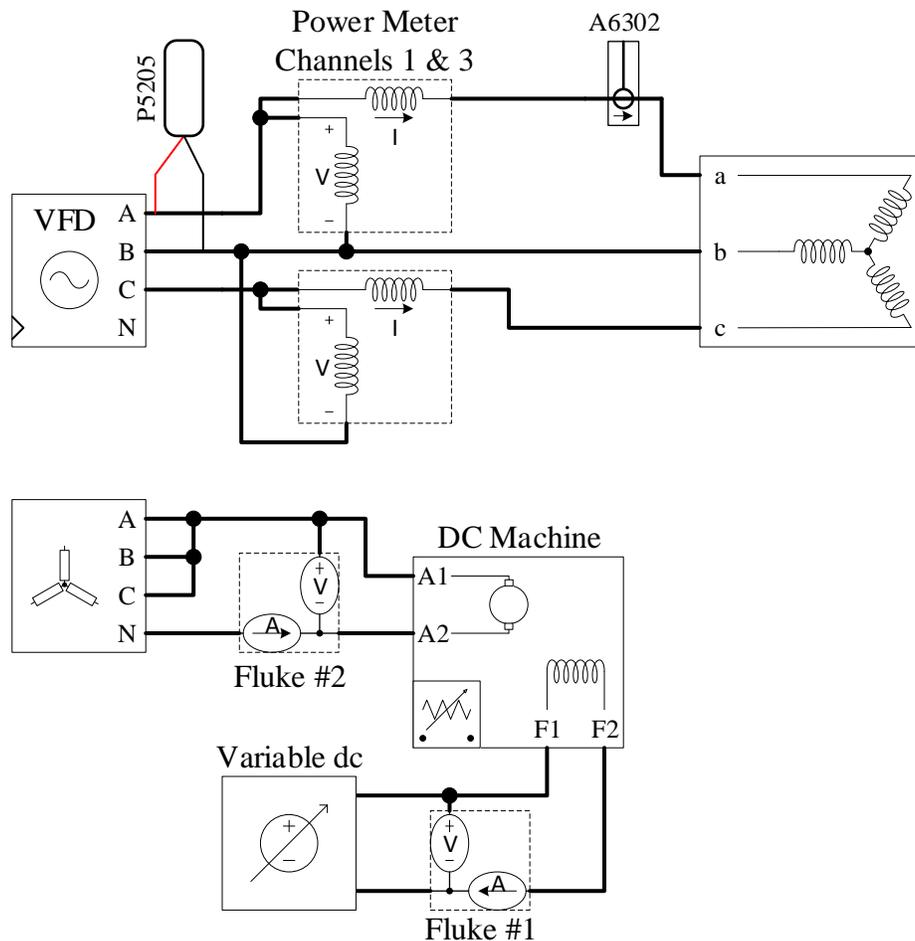


Figure 8: Connection diagram for VFD experiment with induction motor.

are turned off, and have the TA check them before you turn on. After you turn the VFD on, connect to it<sup>1</sup> and set the mode to open-loop, no slip compensation.

Enter a commanded VFD frequency of 25 Hz and press START DRIVE. Measure the speed with the handheld tachometer. This is the no-load speed.

Turn on the variable dc and increase it until the VFD current (measured by the Yokogawa) shows 2.0 A. Record the Yokogawa data, the speed measured with the handheld tachometer, and the Fluke data.

In LabView, on the oscilloscope tab, capture a waveform. (Be sure that the current scaling is set properly first.) Save both the waveform and the FFT. The FFT should indicate a component at 25 Hz; a component at the switching frequency, 8 kHz; and sidebands around multiples of the switching frequency.

On the oscilloscope or the oscilloscope tab, zoom in on the waveform until you can see five to ten PWM cycles on the screen. It will be most interesting if you are near the point where the voltage goes from predominantly negative to predominantly positive or vice versa. Pan along the waveform and observe the variation in the voltage and current waveforms. You

<sup>1</sup>If a communication error occurs, restart the LabView program. If the error persists, ask for assistance.

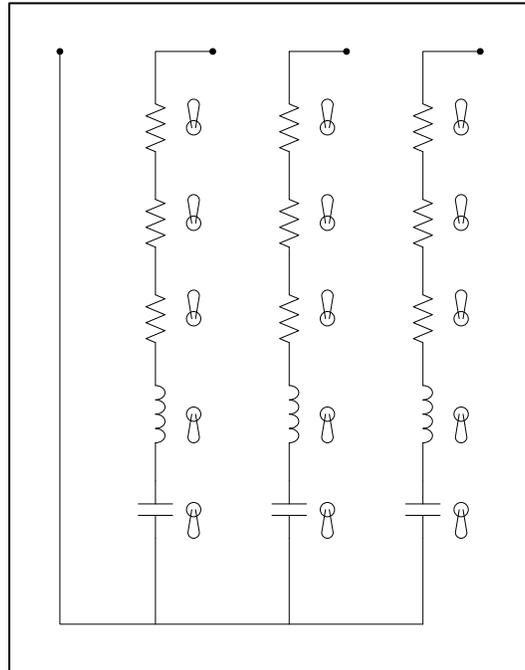


Figure 9: Load box settings for experiment.

may wish to save a few scope images. When you are done, return to the original timescale.

Now, perform some load sweeps at 15 Hz, 30 Hz, 45 Hz, 60 Hz, and 75 Hz. At each frequency, vary the variable dc source from zero up to the point where either the VFD current reaches 2.8 A or the variable dc source maxes out, whichever comes first. Take about five load points over this range. At each point, record the Yokogawa data, Fluke data, and speed (handheld tachometer). Reduce the variable dc source to zero before changing frequency.

After completing all of the load sweeps, set the commanded frequency to zero and stop the VFD. Enable slip compensation. Then repeat the 30 Hz load sweep. When you are finished, reduce the variable dc source to zero, the commanded frequency to zero, and stop the VFD.

### 3.1.1 Optional: RFC-A Mode

Switch to RFC-A sensorless mode. Give a speed command of 900 rpm and perform a load sweep.

Reduce the variable dc back to zero and turn off. Sweep the speed command down to 100 rpm in 100 rpm increments. At each speed command, check the speed accuracy with the handheld tachometer. Also record the frequency reported by the Yokogawa.

## 3.2 Week 2: Permanent Magnet Synchronous Motor (Servo)

Connect as in Fig. 10. Set the load box as shown in Fig. 9. Make all of the connections while the VFD and variable dc are turned off, and have the TA check them before you turn

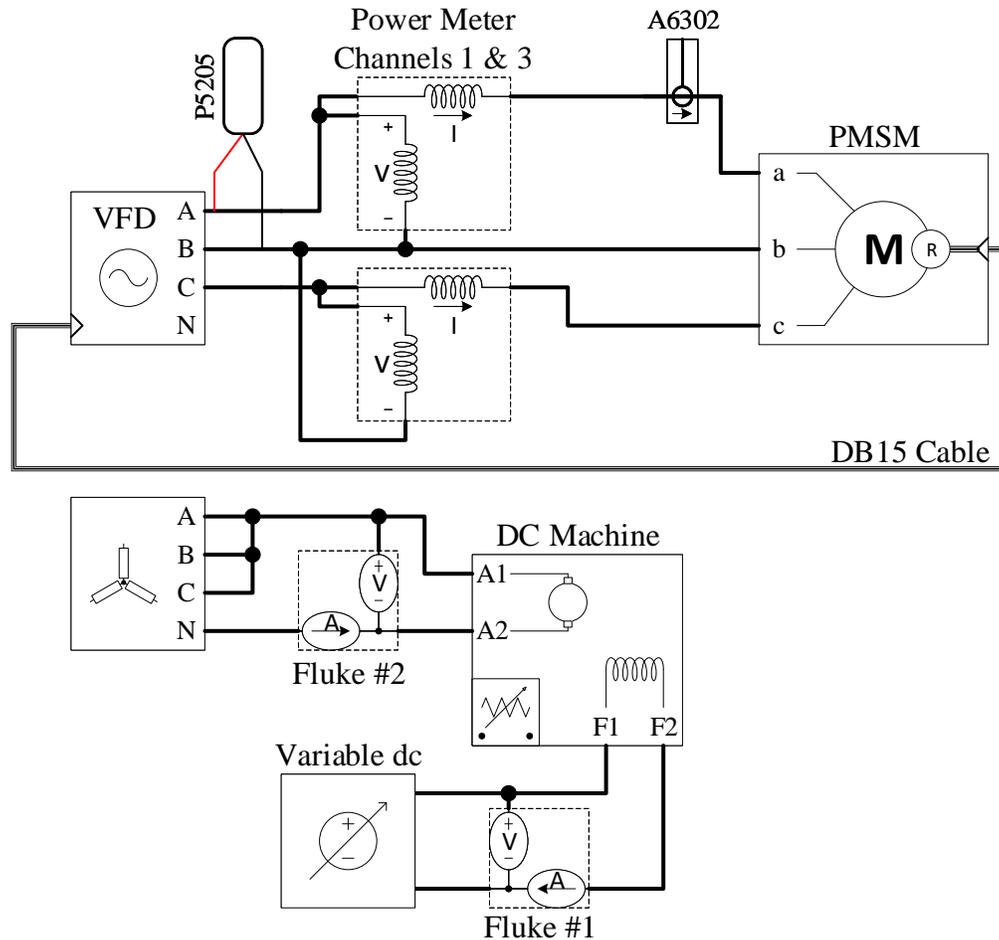


Figure 10: Connections for basic PMSM experiment.

on. After you turn the VFD on, set the mode to **RFC-S** operation (Rotor Flux Control for Synchronous). The parameters should be set properly for the PMSMs that we have (Nidec 089EDA300BAECA).

Enter a commanded speed of 1500 rpm and press Start. Turn on the variable dc and increase it until the VFD current (measured by the VFD or Yokogawa) shows 1.0 A. Record the Yokogawa data, the speed measured with the handheld tachometer, and the Fluke data.

Stop the oscilloscope. In LabView, on the oscilloscope tab, save both the waveform and the FFT. The FFT should indicate a component at about 30 Hz; a component at the switching frequency, 8 kHz; and sidebands around multiples of the switching frequency.

On the oscilloscope, zoom in on the waveform until you can see five to ten PWM cycles on the screen. Pan along the waveform and observe the variation in the voltage and current waveforms. You may wish to save a few scope images. When you are done, return to the original timescale and start the oscilloscope. Make note of any differences between PMSM waveforms and those waveforms observed in the previous induction machine VFD experiment.

Now, perform some load sweeps at 750 rpm, 1500 rpm, and 2250 rpm. At each speed,

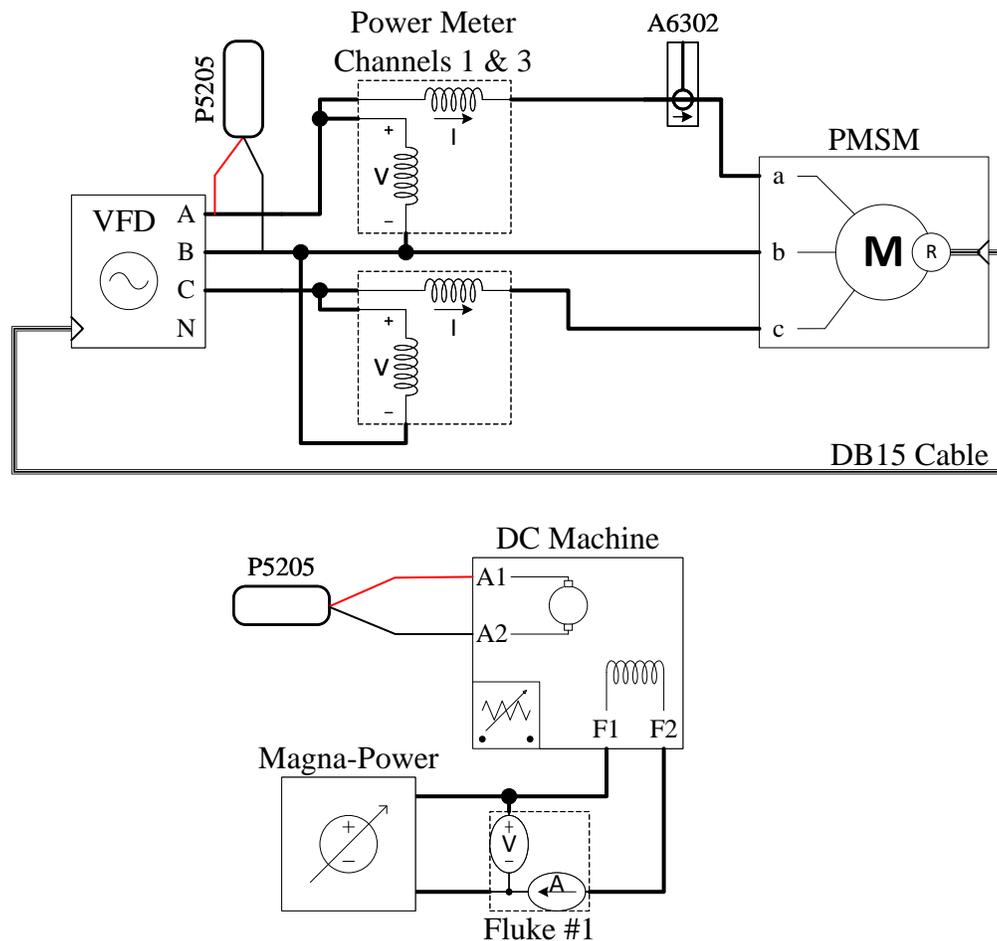


Figure 11: Connections for PMSM step-response experiment.

vary the variable dc source from zero up to the point where the VFD current is 3.44 A. Take about five load points over this range. At each point, record the Yokogawa data, Fluke data, and speed (handheld tachometer). Reduce the variable dc source to zero before changing speed.

When you have finished the load sweeps, set the speed command to zero, stop the VFD, and turn off the variable dc.

### 3.2.1 Step Response

Re-connect as in Fig. 11. On the oscilloscope, we will only be looking at the voltage. We are essentially using the dc generator as a tachometer, that is, using the relationship between its generated voltage and its speed to enable us to dynamically measure speed. Thus, we are operating the dc machine at no load, so that current through its armature does not distort measurements. The measured voltage will have significant ripple, though, due to the relatively small number of armature slots and commutator segments. Use the middle of the ripple as your measurement point.

First, we need to characterize the dc generator. Set the Magna-Power to 150 V, 500 mA. Make sure the voltage channel of the oscilloscope that you are using is set to dc coupling and 25 V per division. Record the mean of the measured armature voltage from the oscilloscope; it should be zero, but will be non-zero due to probe offsets. Then sweep the speed command for the VFD in increments of 100 rpm up to 1500 rpm, recording the measured armature voltage at each point.

Now, set the speed to 500 rpm. On the oscilloscope, set the trigger source to the channel you are using to measure armature voltage. Adjust the trigger level to approximately the voltage that you measured for 1000 rpm. Change the oscilloscope triggering to “normal” (instead of “auto”) and the horizontal position to the middle. Set the timebase to 100 ms per division. At this point, the oscilloscope should appear to be frozen.

Type in a speed of 1500 rpm. The oscilloscope should trigger and show a step response. Stop the oscilloscope and save the waveform (both image and data). Use cursors to measure the rise time. The standard metric is 10% to 90%: whatever the difference between the two steady-state values, the cursors should be at the 10% and 90% points. If there is any overshoot, measure that as well. Save the scope data for later processing, too.

We would now like to measure the step-down response. Change the trigger settings on the oscilloscope to be on the falling edge and start the scope again. Enter a speed of 500 rpm and again save the waveform, measure the fall time, and measure any undershoot. Save the scope data for later processing, too.

When you are satisfied with your step-up and step-down response measurements, set the oscilloscope back to “auto,” rising edge triggering.

## 4 Calculations and Question

### 4.1 Induction Machine Experiment

1. Evaluate the oscilloscope results (time-domain and FFT) in comparison to your expectations, given the discussion earlier in this document.
2. For each load sweep without slip compensation, plot torque vs. speed. See discussion below regarding the calculation of torque.
3. For the load sweep with slip compensation, plot speed vs. torque. Determine the speed regulation, defined as

$$SR = \frac{n_{no\ load} - n_{full\ load}}{n_{full\ load}}$$

4. Plot actual speed vs. commanded speed for sensorless vector mode. Determine the accuracy of the controller. Comment on any unexpected behavior.

### 4.2 PMSM Experiment

1. Compare the time-domain and FFT results of the voltage and current for the PMSM to your previous results on the induction machine.

2. Plot load power vs. speed for the different speed settings. Also plot load power vs. VFD current for the different speed settings. Explain the shapes and scales of the various curves.
3. Use the generator measurements to determine a relationship between armature voltage and speed, of the form  $n = k \times V_a + n_0$ . Use this relationship to convert the saved oscilloscope waveforms to speed vs. time and plot.
4. Compare the step-up and step-down responses to speed commands. Considering that these motors are often used for positioning applications, what conclusion can you draw regarding system-level design?

### 4.3 Computing Torque (IM Only)

In our dynamometers, there are no direct torque measurements. The following method will give a useful approximation for induction motor experiments.

From previous experiments, you should have a value for  $R_1$ , the stator resistance. If you do not have it, you should obtain it from someone who has used your specific motor (ideally), or perform a test to obtain it.

The first test point in each load sweep is with zero field current on the dc machine, so presumably the mechanical load is nearly zero. There will be some friction and windage that are unavoidable, but hopefully small enough to neglect. At this test point, you should have values for  $P_{no\ load}$  (total three-phase power into the induction motor) and  $I_{no\ load}$  (line current into the induction motor). Use these to find:

$$P_{core} = P_{no\ load} - 3I_{no\ load}^2 R_1 \quad (8)$$

$P_{core}$  will also include the friction and windage terms.

At another arbitrary operating point, you will measure  $P$ ,  $I$ , and  $n$ . Calculate as follows:

$$P_{gap} = P - 3I^2 R_1 - P_{core} \quad (9)$$

$$s = \frac{n_s - n}{n_s} \quad (10)$$

$$P_{mech} = (1 - s)P_{gap} = \frac{n}{n_s} P_{gap} \quad (11)$$

$$\omega_m = n \times \frac{\pi}{30} \quad (12)$$

$$T_{mech} = \frac{P_{mech}}{\omega_m} = \frac{P_{gap}}{\omega_s} \quad (13)$$

Now you can plot  $T_{mech}$  vs. speed.