

EE3501, Experiment 9

DC Machines

Jonathan Kimball, August 31, 2020

Abstract

This experiment explores dc machines, with a particular focus on generator behavior. Previous experiments have used a dc machine as a load or source for other motors or generators. In this lab, the emphasis will be on the dc side of the dynamometer. A synchronous motor will be used as the prime mover.

1 Introduction

DC machines may be used as either motors or generators. As motors, they are typically used where speed control is needed as they are the easiest to control. As generators, they are used wherever a dc source is needed, e.g., to power other dc motors. This experiment will explore a *self-excited* generator.

Synchronous motors are used in applications such as textile mills where constant speed operation is critical. Most small synchronous motors contain squirrel cage bars for starting. In this experiment, synchronous motor starting is demonstrated. After starting, the motor is locked into synchronism by applying a rotor field current. The field current may be varied to adjust the reactive power consumption or generation. For this experiment, you will use the synchronous motor as the prime mover for the dc generator.

Most synchronous motors cannot be line-started (started by simply applying rated voltage and frequency to the armature) if the rotor field is active. “Starting” implies that the speed is zero. When rated voltage and frequency are applied to the armature, the stator field rotates at synchronous speed n_s . However, the rotor has inertia and so will initially remain stationary. As the stator field rotates, the torque produced will be alternately positive and negative, with zero average, as illustrated in Figure 1. The motor will vibrate but will not accelerate towards synchronous speed.

To facilitate starting, the synchronous motor has a set of short-circuited bars, called *dampers windings* or *amortisseur windings*. A short-circuited coil is essentially the same as a squirrel-cage rotor in an induction motor. Thus, for starting purposes, the synchronous motor behaves like an induction motor.

Like any induction motor, the speed can never actually reach synchronous speed. If the losses due to friction and windage are low, the speed will come close, though (a very small slip). At this time, if the field winding is energized, a brief time of positive torque is sufficient to make the rotor “lock in” to the stator flux wave. From this point forward, the machine will operate as a synchronous machine.

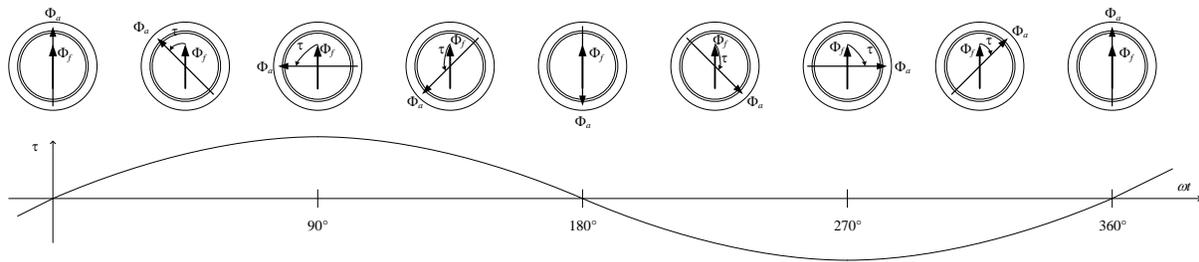


Figure 1: Torque evolution when trying to line-start a synchronous motor with field active. Torque (τ) is proportional to the sine of the angle between stator flux Φ_a and rotor flux Φ_f , with a zero average.

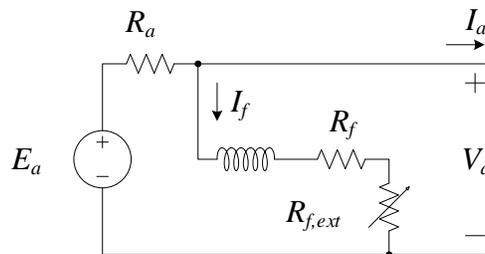


Figure 2: Linear model of shunt-wound dc machine.

Note: The “synchronous” machines used in the Missouri S&T lab are actually wound-rotor induction machines. Therefore, it is reasonably safe to leave the “damper winding” active for a long duration. Typically, though, it is best to use the damper winding for as short a time as possible.

Self-Excited DC Generator: After the synchronous motor is started and operating normally, it may be used as the prime mover for a generator, substituting for an engine or turbine. A self-excited generator is shunt-wound and the field current is supplied by the armature generated voltage. The equivalent circuit of Figure 2 is a linear approximation that is useful but does not show two key nonlinearities.

Generated voltage E_a is proportional to flux Φ_d and speed ω_m ,

$$E_a = K_a \Phi_d \omega_m \quad (1)$$

In most situations, we may assume that

$$\Phi_d = K_f I_f \quad (2)$$

That is, the flux is linearly dependent on the field current. In reality, though, the saturation and hysteresis of the steel used to construct the machine add an offset Φ_{rem} and limit the generated voltage. In addition, when current flows through the armature windings, the steel enters saturation early, an effect called *armature reaction*. All of these effects are illustrated in an exaggerated fashion in Figure 3. Also illustrated is a load line, which is the resistive relationship between E_a and I_f due to R_f and $R_{f,ext}$.

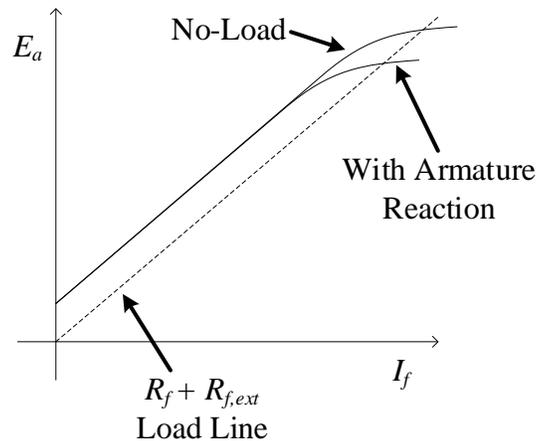


Figure 3: EXAGGERATED characteristic of shunt-wound dc machine.

If the machine is properly designed and the correct resistance is used, the self-excited dc generator will operate at the intersection of the load line and one of the other curves, depending on the load.

2 Laboratory Software

In this set of experiments, you will use two Flukes for dc measurements, the Yokogawa to measure ac voltage and current, and the Magna-Power rack-mounted supply to provide dc current to the SM field winding. Use Flukes #1 and #2, with #1 measuring dc voltage and current and #2 measuring dc current only. Set the Yokogawa to 3P3W mode (the two-wattmeter method).

3 Laboratory Experiment

Connect the machines as in Figure 4. Make sure that the three-phase mains switch is off, and that the **switch on the synchronous machine connection box is off**. Set the Magna-Power to provide 2.5 A. As initially connected, this current will flow through a shorting wire that connects ar to br and cr. Start with the dc machine field rheostat turned to maximum resistance (all the way **clockwise**).

Turn on the three-phase mains. The lamps on the synchronous machine connection box should light up. Turn on the switch on the connection box to short the lamps and start the synchronous machine. It will start immediately due to the shorted coil on the rotor. Measure the speed with a handheld tachometer. Record the stator voltage, current, and frequency.

Remove the shorting wire indicated so that ar is independent. Now the 2.5 A source will flow through the SM field winding. Measure the speed with a handheld tachometer. Record the stator voltage, current, and frequency.

Now take data points to reproduce Figure 3. Record the field current and armature voltage with the field rheostat at maximum resistance. Then reduce the resistance and

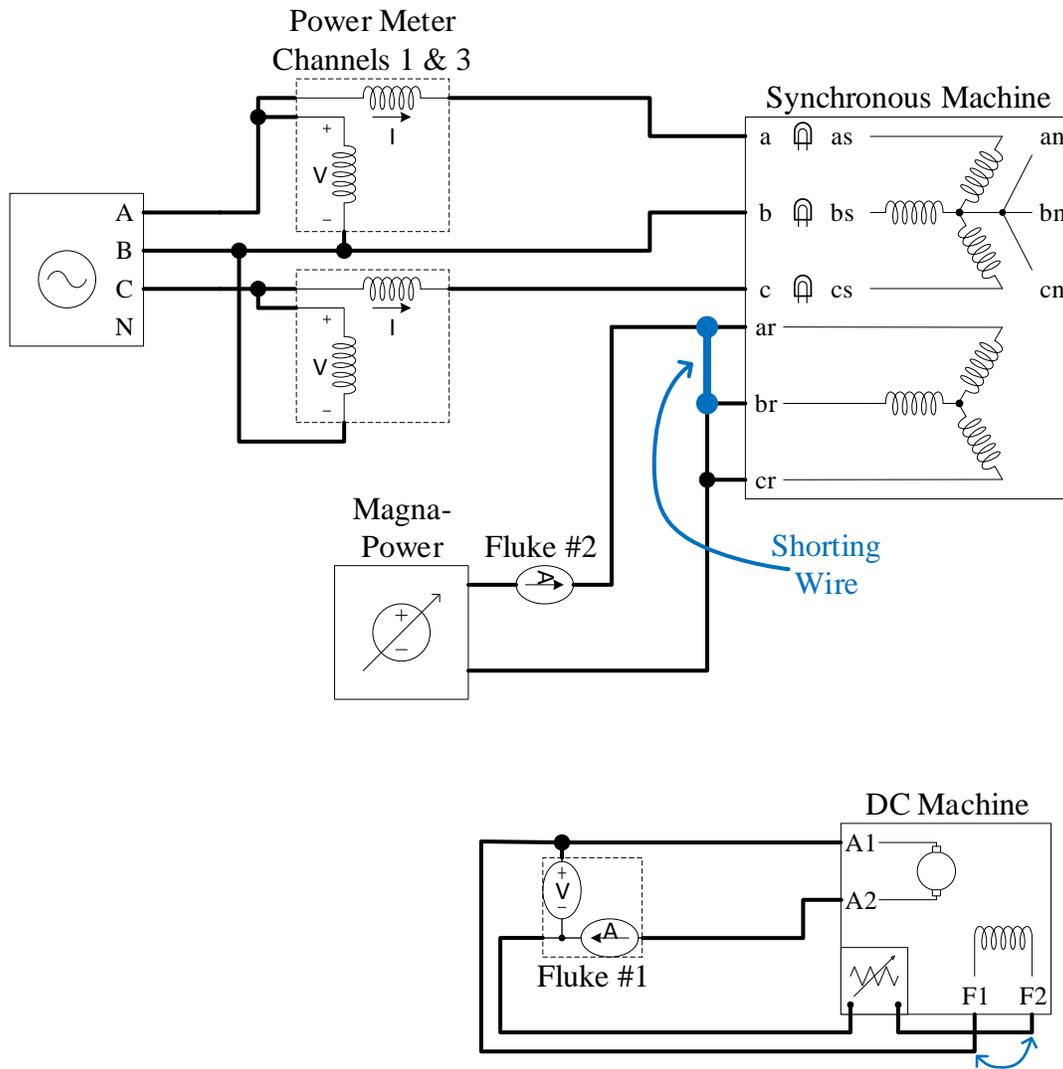


Figure 4: Connection diagram for experiment.

record field current and armature voltage about every 10 V. Continue until you reach either 200 V on the armature or minimum resistance of the rheostat. If the armature voltage never rises above 10 V, swap the leads indicated with the double-ended arrow (F1 and F2) and start over.

Shut down in the following order:

1. Reduce commanded SM field current to zero.
2. Turn off the switch on the SM connection box.
3. Turn off the three-phase mains.
4. Turn off the Magna-Power.

4 Calculations and Question

1. Calculate the synchronous speed of a four-pole machine with the line frequency measured (approximately 60 Hz). Compare to the speeds measured both before and after removing the shorting wire on the SM field. If you observed any significant differences in voltage or current, comment on them.
2. Plot the field characteristic (generated armature voltage vs. field current) for the generator.
3. Determine the total resistance (field winding resistance plus external resistance) that would be needed for steady-state operation at 120 V.