EE35x1, Experiment 04: Synchronous Machines

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Abstract

Over the course of two laboratory sessions, this experiment explores wound-field synchronous machines (SMs). SMs are commonly used as generators, but are also used as motors (particularly in large systems). During the first week, students will find the parameters of the machines in the laboratory. Then in the second week, students will connect the SM to the line and operate it as a generator to explore its behavior.

1 Introduction

Wound field synchronous machines comprise a dc winding on the rotor (field) and an ac winding on the stator (armature). The field winding is excited to produce flux. The shaft is turned by a *prime mover*, that is, a source of mechanical power. As a result, ac voltage is induced in the armature.

An SM is synchronous in the sense that the generated voltage is directly related to, and synchronized with, the shaft speed. Typically, electrical frequency f_e is expressed in hertz (Hz) and mechanical speed n is expressed in revolutions per minute (RPM). The synchronous machine always has an even number of poles. Then

$$n = \frac{120 f_e}{poles} \tag{1}$$

The factor of 120 is because of the even number of poles (factor of 2) and seconds in a minute (60). Electrical frequency may also be given in $\mathrm{rad} \cdot \mathrm{s}^{-1}$:

$$\omega_e = 2\pi f_e \tag{2}$$

The synchronous generator steady-state per-phase equivalent circuit is given in Figure 1. Typically, the line-to-neutral armature terminal voltage is taken as a reference, so

$$\hat{V}_a = V_a \underline{/0} \tag{3}$$

$$\hat{E}_{af} = E_{af} \underline{/\delta} \tag{4}$$

$$\hat{I}_a = I_a \underline{/-\theta} \tag{5}$$

Armature resistance R_a is neglected and $X_s = \omega_e L_s$ is the stator synchronous reactance. Often, we drop the "f" subscript and simply write the generated voltage as $\hat{E}_a$. Its angle, δ is called the *torque angle* or *power angle*. All armature signals are ac with a frequency f_e and all field signals are dc.

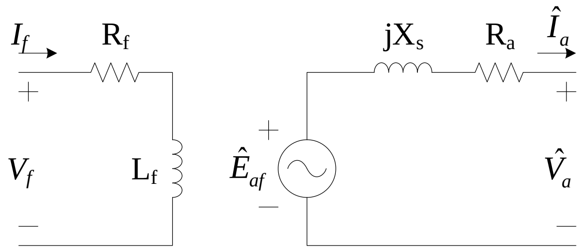


Figure 1: Per-phase equivalent circuit for synchronous generator.

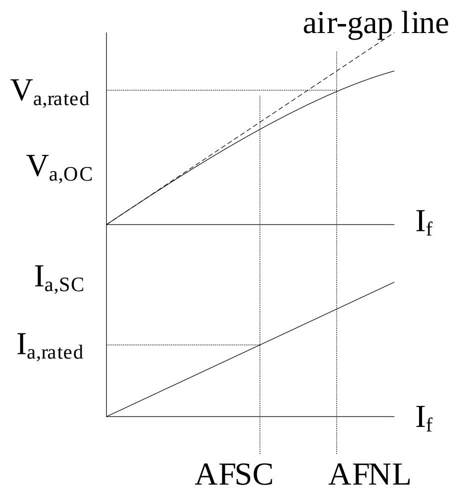


Figure 2: Typical results for open-circuit/short-circuit testing of a synchronous generator.

1.1 Determining Parameters

There are two characteristics to determine: the relationship between generated voltage and field current, and the value of synchronous reactance. The magnitude of the generated voltage is given by

$$E_{af} = \frac{\omega_e L_{af} I_f}{\sqrt{2}} \tag{6}$$

During open-circuit conditions, $V_a = V_{a,OC} = E_{af}$. So a standard test to perform is to operate the generator at rated speed and measure its open-circuit voltage as a function of field current. One would expect a linear relationship. However, steel is not linear, so L_{af} is not constant[1]. A typical test result is shown in Figure 2. The point on the axis labeled "AFNL" is the field current corresponding to an open-circuit voltage equal to the rating ("amperes-field-no-load"). The air gap line is the linear extrapolation of the low-field-current characteristic.

During short-circuit conditions,

$$I_a = \frac{E_{af}}{X_s} \tag{7}$$

That is, we know the generated voltage and can measure the armature current, so we can find

[1] Also, please note that L_{af} is different from, and not related directly to, L_f or L_s

the synchronous reactance. A typical approach is to sweep the field current and measure open-circuit voltage, and then use the same field current values for short-circuit current. Then

$$X_s = \left.\frac{V_{a,OC}}{I_{a,SC}}\right|_{I_f=AFNL} \tag{8}$$

Remember that we typically rate and measure three-phase voltages **line-to-line** but that the per-phase equivalent circuit is **line-to-neutral**, so you will typically need to divide measured voltage by $\sqrt{3}$.

For low values of field current, the machine is unsaturated and the synchronous reactance is denoted $X_{s,u}$. If the armature resistance is included, the exact reactance is

$$X_{s,exact} = \sqrt{\left(\frac{V_{a,OC}}{I_{a,SC}}\right)^2 - R_a^2} \tag{9}$$

In most practical machines, the difference between (8) and (9) is far below 1%.

Another interesting parameter is the short-circuit ratio (SCR), which quantifies the short-circuit behavior of the machine. Just as AFNL is the field current that gives rated voltage under open-circuit conditions, AFSC (amperes-field-short-circuit) is the field current that gives rated current under short-circuit conditions. Then

$$SCR = \frac{AFNL}{AFSC} \tag{10}$$

SCR is dimensionless. It can be shown that

$$X_s = \frac{1}{SCR}\frac{V_{a,rated}}{I_{a,rated}} \tag{11}$$

(Use the saturated reactance.)

Please note: If you use the saturated synchronous reactance in your circuit analysis, the generated voltage you use must be the linear approximation obtained from a line through the origin and the $(AFNL, V_{a,rated}$ point.

1.2 Line Synchronization

So now we have the parameters of a generator. We need to connect it to the grid to actually generate some power. Figure 3 illustrates the conceptual setup. The system consists of:

- A prime mover, such as a turbine, engine, etc. In the lab, we use a dc motor. The mechanical power input is controlled with a *governor*. We use a rheostat (variable resistor).
- The synchronous generator.
- An *exciter* to control the field. In the lab, we use a dc power supply.
- A three-phase contactor. This is essentially three large switches that open and close together.

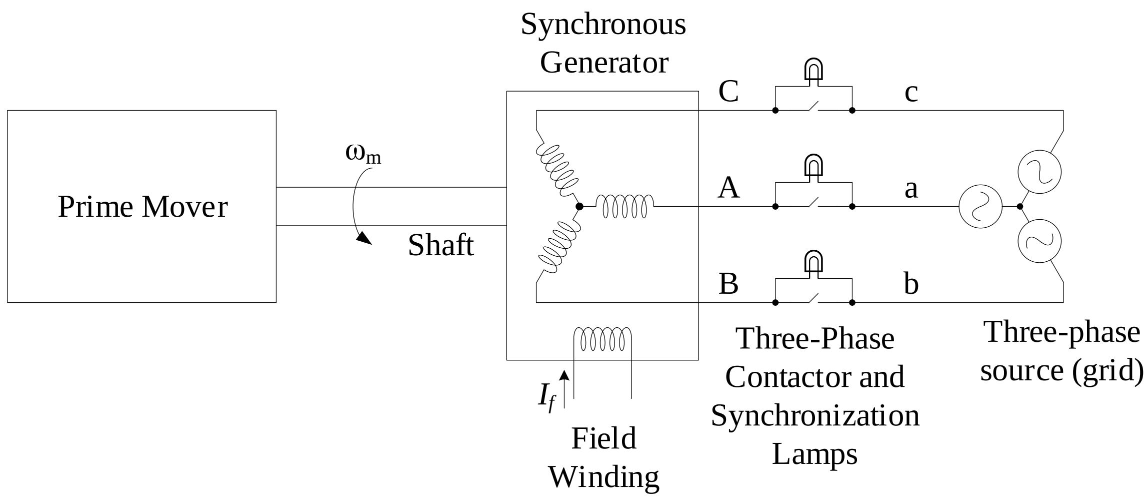


Figure 3: Circuit for line synchronization of a synchronous generator.

- Synchronization lamps. As illustrated, we are using the dark lamp method. The difference between the generator voltage and the grid voltage is applied to the lamps.
- The three-phase grid.

Before closing the contactors, the generator voltage must match the grid voltage in magnitude, frequency, and phase (and phase sequence). When all three conditions are met, the voltages across the contactors will be zero, and the lamps will go dark. Recall that the frequency of the voltage depends on the speed, according to

$$f_e = \frac{poles}{2}\frac{\omega_m}{2\pi} \tag{12}$$

The magnitude of the voltage depends on the field current.

The final step is to match the phase (and phase sequence) precisely. Let's assume that the speed of the generator is *close* to matching the equivalent to the grid frequency. Then the apparent phase difference between the generator and the grid will go from very large to very small, and all three lights will blink together. When they are all dark, it is safe to close the contactor.

If the phase sequence of the generator is different from the grid, the lamps will blink one at a time. In that case, swap two phases and the phase rotation will be reversed.

1.3 Generator Behavior

So now we have a generator, whose parameters we know, connected to the grid. If we inject some mechanical power via the prime mover, we can deliver some active power to the grid. At the same time, we can produce or absorb reactive power by adjusting the field current. From the per-phase equivalent circuit of Figure 1,

$$P = 3V_aI_a\cos\theta \tag{13}$$
$$Q = 3V_aI_a\sin\theta \tag{14}$$

Neglecting armature resistance, we can show that

$$X_s I_a \cos\theta = E_{af} \sin\delta \tag{15}$$

Therefore, for constant active power P, both $I_a \cos\theta$ and $E_{af} \sin\delta$ are constant. Also, from KVL,

$$\hat{E}_{af} = \hat{V}_a + jX_s\hat{I}_a \tag{16}$$

These relationships are all combined to draw phasor diagrams for three operating conditions in Figure 4. In Figure 4a, the machine is *producing* VARs; we call this *overexcited*. This is the same behavior as a capacitor, so it is sometimes referred to as leading power factor[2] or capacitive behavior.

In Figure 4b, the machine is operating at *unity* power factor. Then in Figure 4c, the machine is *consuming* VARs; we call this *underexcited*. This is sometimes called lagging power factor or inductive behavior.

Notice in all three diagrams that the grid voltage $\hat{V}_a$ is constant, as are $I_a \cos\theta$ and $E_{af} \sin\delta$. However, as E_{af} varies, so do δ and θ, and therefore I_a. A V curve, such as Figure 5, graphically relates I_f or E_{af} to line current I_a. The "pf = 1" curve[3] separates the underexcited (left) portion from the overexcited (right) portion.

2 Laboratory Software

In this set of experiments, you will use two Flukes to measure dc current, the Yokogawa to measure ac voltage and current, and either the Tenma benchtop supply or the Magna-Power rack-mounted supply to provide dc current to the 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). You will also use a P5205 probe with the oscilloscope in just the first test.

3 Laboratory Experiment

3.1 Week One: Finding Parameters

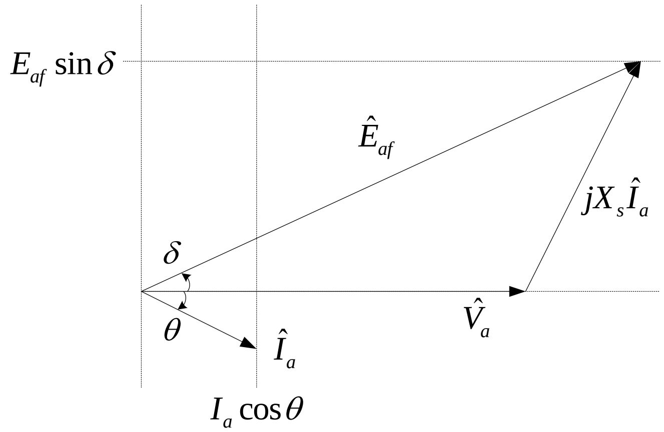
Connect the machines as in Figure 6 to perform an open-circuit test. For this set of tests, you will use the Tenma because we are operating at very low currents. Set its voltage limit to 20 V and command currents, starting from 0 A. **Make sure the switch on the connection box of the synchronous machine is ON.**

With the variac at zero, turn it on. Increase the variable dc to about 60 V. The dc motor should run smoothly. If it does not, reduce the voltage, turn it off, change to the alternative field connection shown at the bottom of Figure 6, and again bring the voltage up.

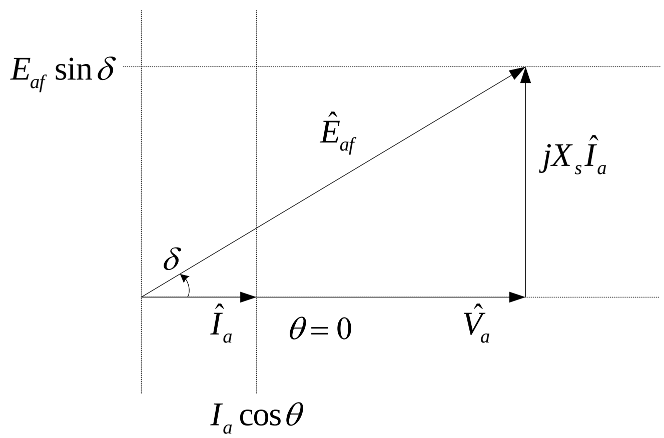
Increase the variable dc to about 150 V. Measure the shaft speed with the handheld tachometer. Adjust the dc voltage until the speed is close to 1.800 krpm. The synchronous

[2]Technically, "power factor" is only a term applied to loads, not sources.

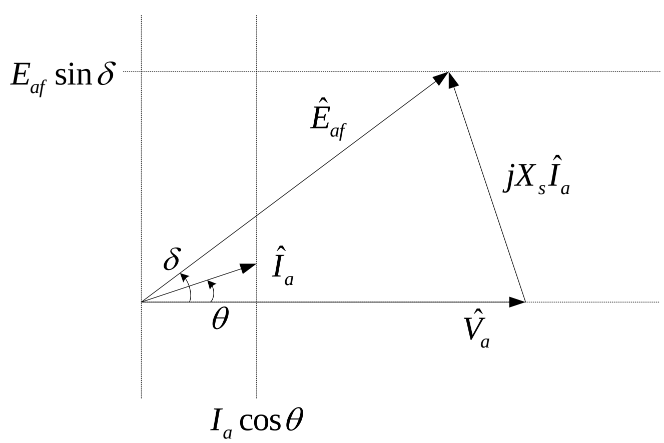
[3]Since power factor is not a proper term here, a better label might be $\theta = 0$. However, "pf = 1" is a common notation.



(a) Overexcited; producing VARs; $\theta < 0$



(b) Unity power factor; $\theta = 0$



(c) Underexcited; consuming VARs; $\theta > 0$

Figure 4: Phasor diagrams for three operating regimes.

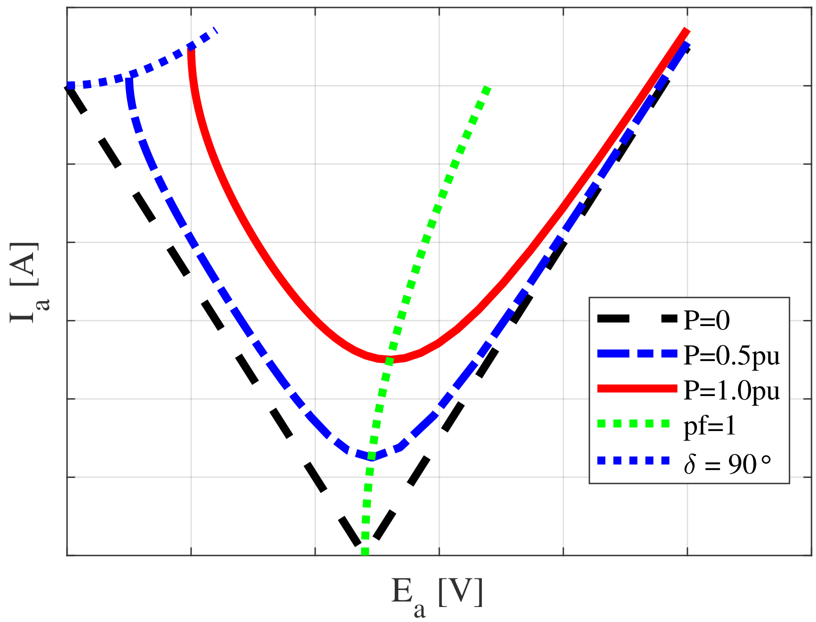


Figure 5: Typical V curves. Also indicated are the unity power factor boundary between underexcited and overexcited, and the $\delta = 90°$ limit beyond which the machine cannot produce the desired power.

machine armature voltage should be slightly nonzero on the oscilloscope. Measure its frequency and compute the number of poles, which must be an even integer.

Increase the Tenma current command (which is the field current of the synchronous machine) to 250 mA and log the armature voltage. Increase the current in increments of 250 mA up to 2.5 A, logging armature voltage so that you can plot the open-circuit characteristic.

Reduce the field current to zero. Add shorting wires to short the armature of the synchronous machine, as indicated in Figure 7. You no longer need the oscilloscope, so you can disconnect it or leave it connected as you choose. As for the open-circuit test, increase the field current in 250 mA steps up to 2.5 A, logging the armature current so that you can plot the short-circuit characteristic.

When you have obtained all the data, reduce the field current (Tenma) and the variable dc to zero and shut everything down.

3.2 Week Two: Grid-Connected Operation

Connect the machines as in Figure 8. **Make sure the switch on the connection box of the synchronous machine is OFF.** Notice that we are using the Magna-Power for the synchronous machine field current, the three-phase mains for the SM armature, and a rheostat in the field connection of the dc machine. Start with the rheostat turned all the way counterclockwise.

Command the Magna-Power to provide a field current of 2.5 A. Switch on and increase the variable dc to about 40 V. If the dc motor does not start, switch off the source panel,

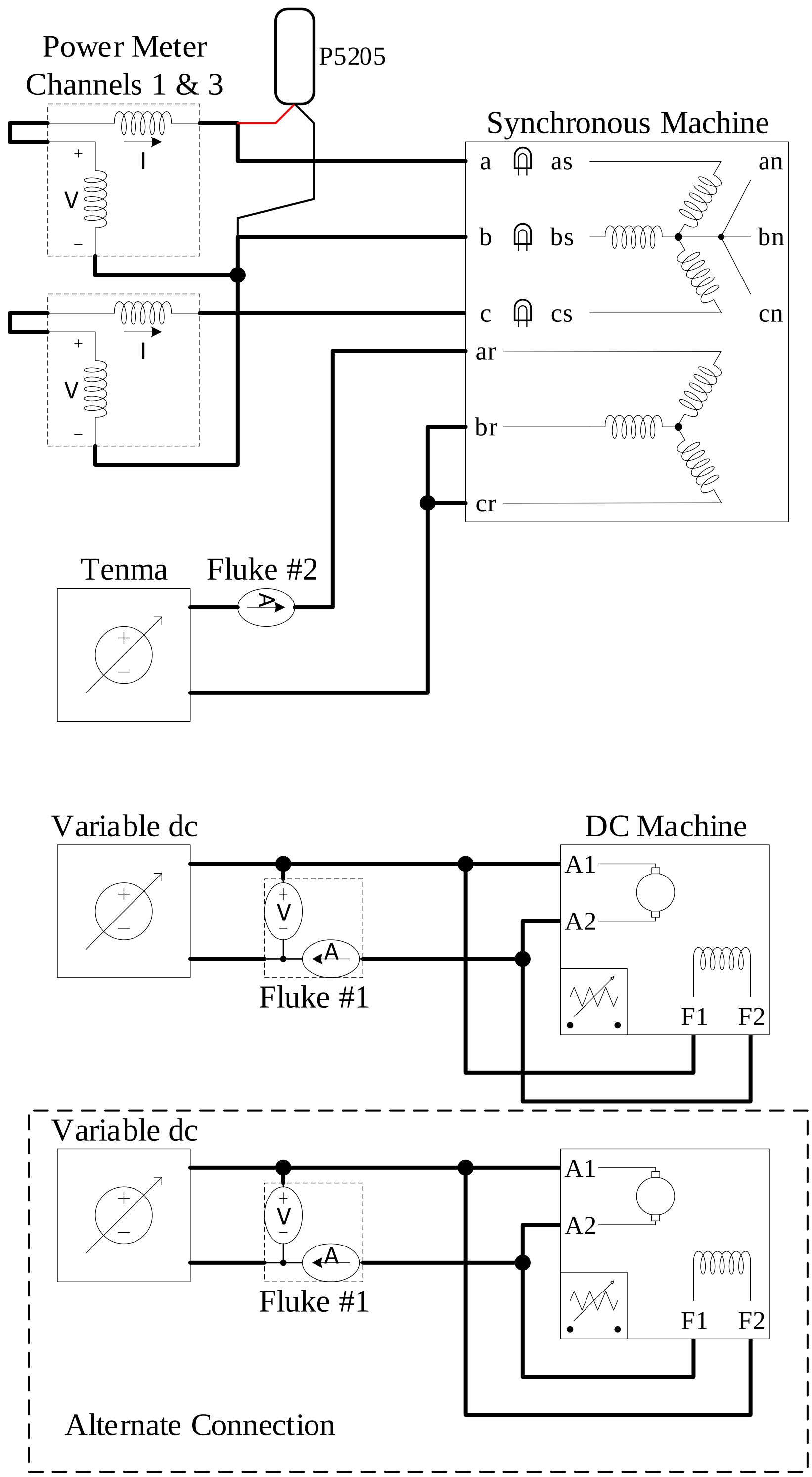


Figure 6: Connection diagram for open-circuit test

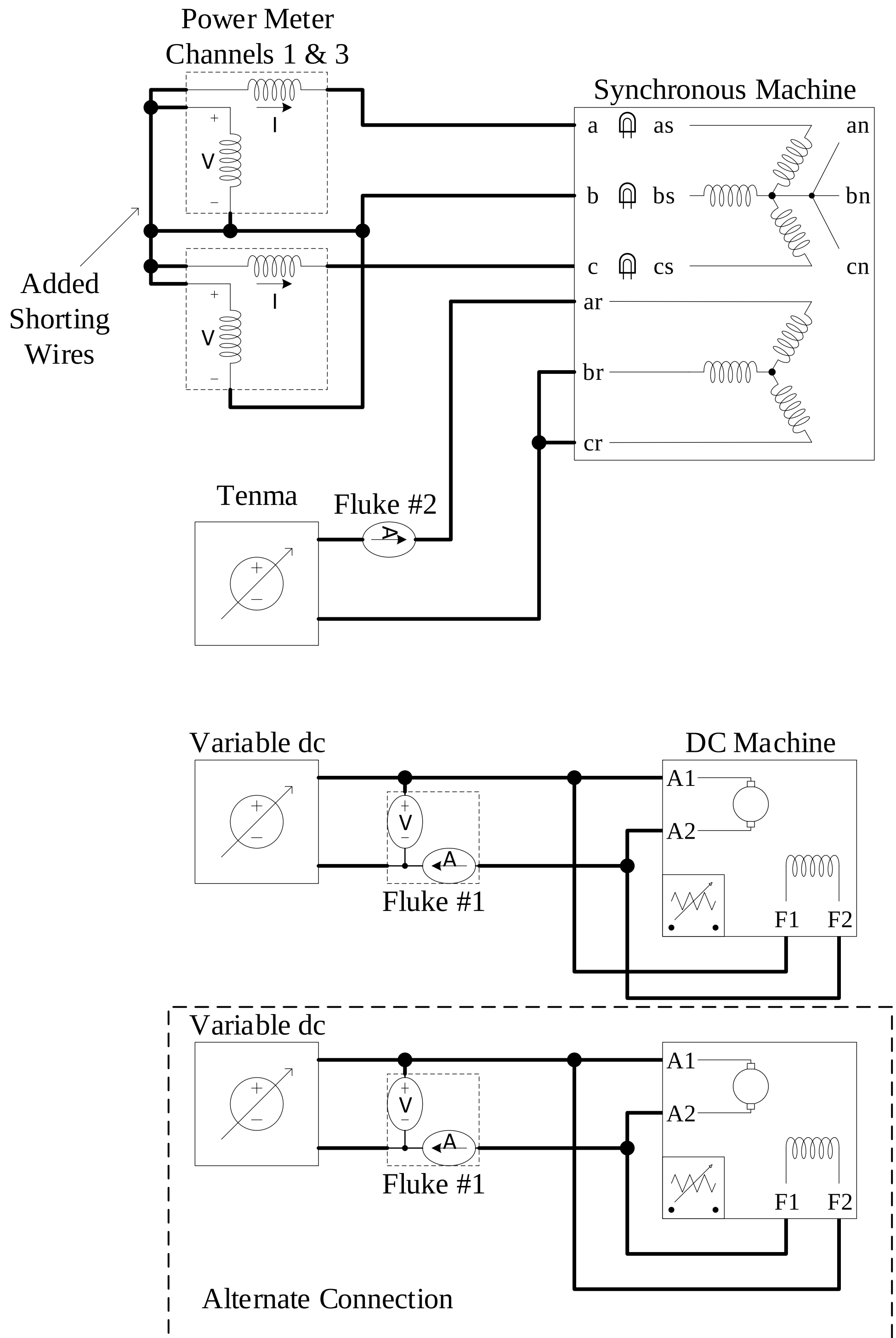


Figure 7: Connection diagram for short-circuit test

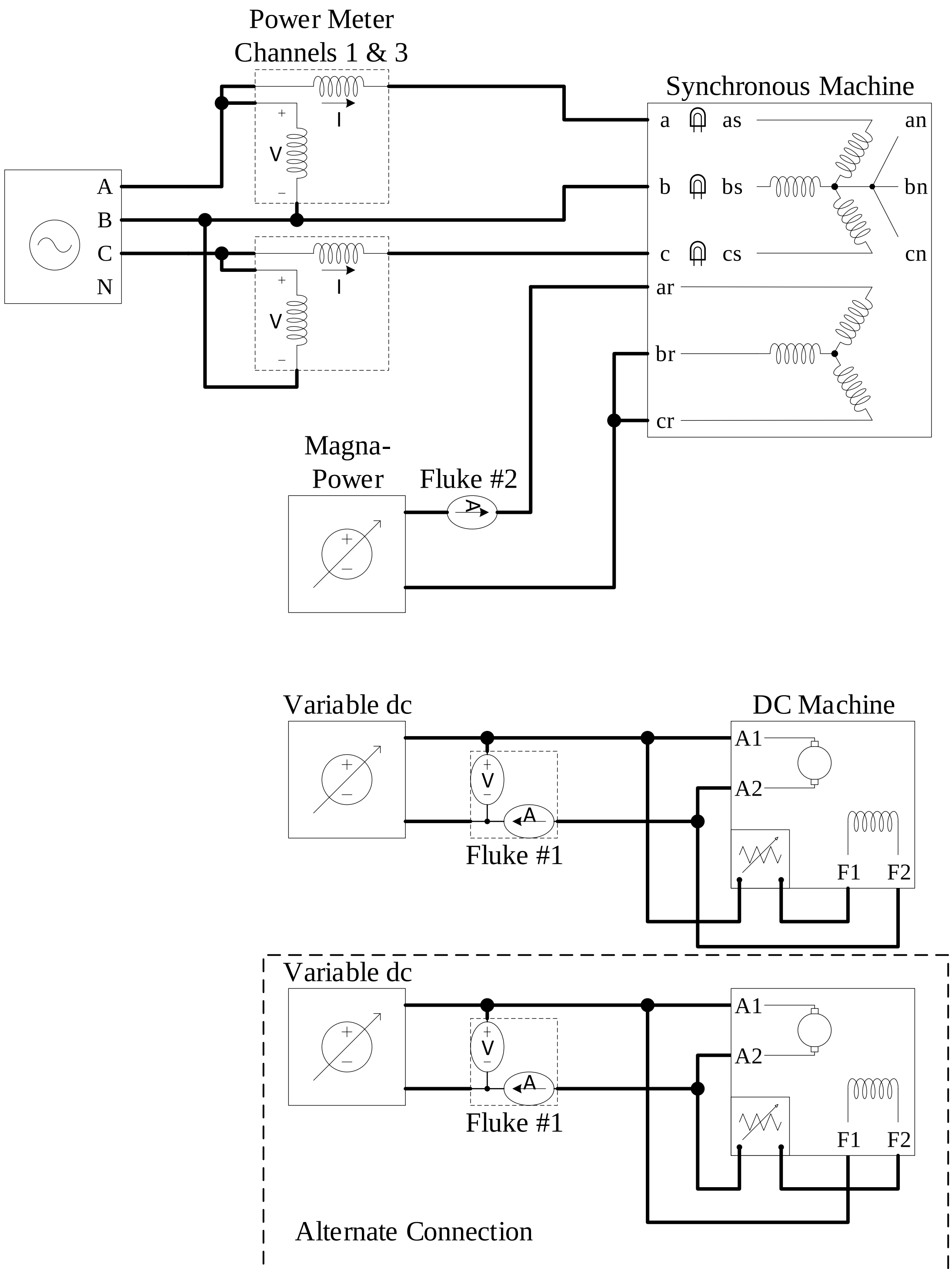


Figure 8: Connection diagram for grid-connected test

swap dc motor terminals F1 and F2 as illustrated, and try again. Once the motor is running, increase the variable dc until the speed is nearly 1.800 krpm. Then turn on the three-phase power to the synchronous machine terminals.

At this point, the three lamps on the synchronous machine should be blinking in synchronism at a low frequency. If instead they are blinking one at a time, alternating, then the phase sequence is incorrect. In that case, bring everything back down to zero, swap terminals B and C of the synchronous machine, and bring the system back up.

Adjust the variable dc so that the three lamps are blinking slowly, indicating that the synchronous machine is nearly synchronized with the grid voltage. **At a time when all three lamps are dark, throw the switch.** This will connect the armature directly to the three-phase mains.

Now that the SM is operating as a generator, you can sweep some V curves. Sweep the Magna-Power current from 1.5 A to 3.5 A in steps of 200 mA, logging the Yokogawa data at each point. This will be your "zero power" curve. Note that the active power will be slightly non-zero, but as close to zero as possible.

The dc motor can now act as the prime mover and deliver some active power to the SM, which delivers that power to the grid. Adjust the rheostat until the generator is producing 50 W. Sweep the SM field current as before. At each point, adjust the rheostat to keep the active power as constant as possible. Finally, repeat the sweep with the generator producing 100 W.

When you are finished, turn everything off in this order:

1. Turn off the variac switch
2. Reduce variac to zero
3. Turn off the three-phase mains
4. Turn off the Magna-Power

4 Calculations and Question

1. Plot the open-circuit and short-circuit characteristics. Also plot the air-gap line, using a few low-field-current points.
2. Using a data point from the linear region (low field current) to compute the unsaturated synchronous reactance, $X_{s,u}$.
3. Based on machine ratings of 208 V and 700 mA, determine the AFNL, AFSC, and short-circuit ratio. Note that this calculation may require interpolation between test data points.
4. Again using the same machine ratings, compute the saturated synchronous reactance, X_s. Also compute a field constant that relates generated voltage to field current (i.e., $E_{af} = K_f I_f$, find K_f).

5. Compute the saturated synchronous reactance using SCR and machine ratings. Compare this result to the direct method of finding X_s from open-circuit voltage and short-circuit current directly.

6. Create two graphs, one for each active power level (i.e., a 50 W graph and a 100 W graph). For each graph, put the SM field current on the x axis and power on the y axis. Plot active and reactive power curves on each graph. The active power curves should be nearly flat (depending on how effectively you adjusted the generated power). Be sure your sign convention corresponds to **generating**.

7. Create V curves for this generator, one graph with all three power levels, with field current as the x axis. Also, using the value of X_s previously measured, compute theoretical curves. Explain the discrepancies.

8. Sketch the phasor diagrams for three operating points on the 100 W curve: one at leading power factor, one at unity, and one at lagging power factor. Use experimental data.