ECEN 460 Laboratory 3, Spring 2025
Synchronous Generator Parameters and Equivalent Circuit, and Operation of the Synchronous Generator Under Load

Objective:

To derive the equivalent circuit of a synchronous generator from the results of the open-circuit and short circuit tests. It also aims to show the relations between the field excitation, rotor speed, the open circuit armature voltage and the short circuit current.

EQUIPMENT

Synchronous machine (1)

DC machine (1)

Multi-meter (3)

Tachometer (1)

Inductive Load (1)

Resistive Load (1)

PROCEDURE

The procedure consists of four steps:

- Open Circuit Test
- Short Circuit Test
- Armature Resistance Test
- Synchronous Generator Under Load

Part A: Open Circuit Test

1) Connect the synchronous machine to operate as a 208 V (line-to-line), 3-phase, Y-connected synchronous generator as shown in Figure 1.

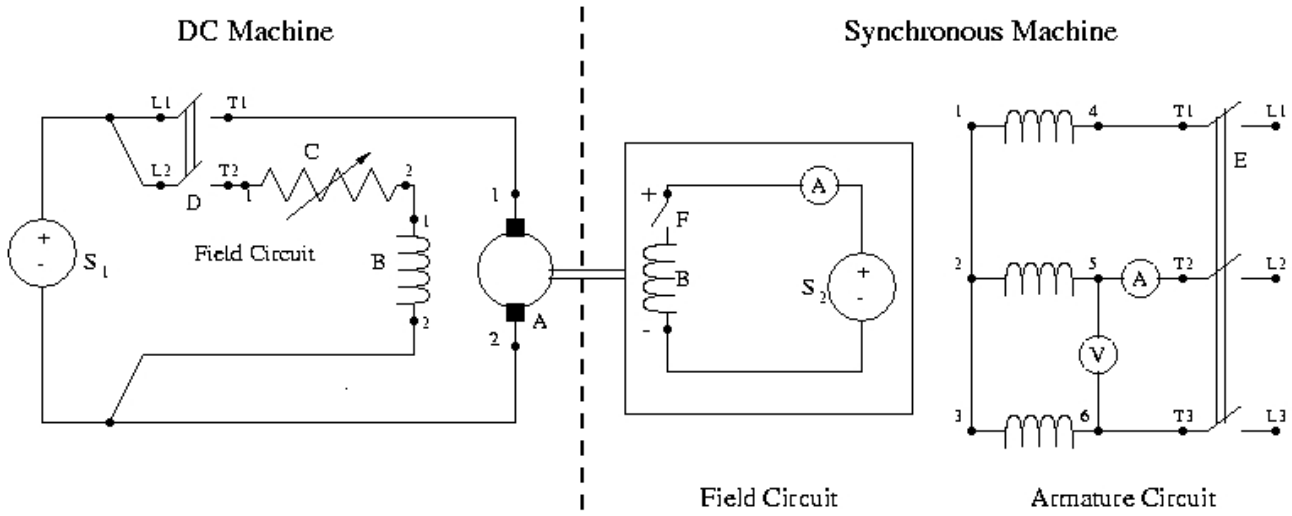

Figure 1

A: Armature	E: 3-ϕ circuit switch
B: Shunt Field	F: Field switch (Left pos.: Start, Right pos.: Syn. Run)
C: Field Rheostat	S_1: 0-125 V, 6A maximum, variable DC voltage source (setting S_1= 125V, constant)
D: DC machine start switch	S_2: 0-150V, 1A maximum, variable DC voltage source

2) Connect the DC machine to operate as a shunt motor as shown in Fig. 1.
3) Adjust the rheostat (C) of the DC motor to be at its maximum value (i.e., turn it **counterclockwise**). Set switch **D** to the **OFF** position. Set switch **E** to the **OFF** position, set **F** to the '**Ind. Start**' position (left).
4) Have the instructor check your machine and meter connections before proceeding.
5) Start the DC motor by switching '**D**' to the **on** position. Gradually increase the S_1 voltage, eventually reaching 125V (DC). Then adjust the speed to 1800 rpm by varying the rheostat 'C'. Keep the speed constant until step 8.
6) Apply field voltage (S_2) to the synchronous machine by switching **F** to the '**Syn. Run**' position (Right). Adjust S_2 in order to get 120% of the rated armature voltage (rated armature voltage is 208 V line-to-line, hence V_{LL} = 208 $\times$1.2 = 249.6 V, V_{LN} = 144 V). Record the voltage at the generator's terminals V_{LL} and its field current I_f. Then tabulate them in Table 1. Check the speed and be sure that it is constant (i.e., 1800 rpm).
7) Obtain six more data points for the open circuit armature voltage and field current by decreasing I_f to 0.60 A, then 0.54 A, 0.50 A, 0.45 A, 0.40 A and 0 A. Record

V_{LL}, I_f and tabulate them in Table 1. ***In order to avoid hysteresis effects, never increase the field current to make minor corrections as you reduce the field current.***

8) Adjust the speed to 1600 rpm by varying the rheostat 'C' and repeat steps 6 – 7. Then tabulate the results in Table 2.
9) Set the field voltage (S_2) of synchronous machine to zero and switch the voltage supply off. Stop the DC motor by first gradually reducing S_1 to zero and then switch 'D' off and wait until the machine stops completely.

Part B: Short Circuit Test

1) Create a 3-phase short circuit across the armature terminals of the synchronous generator as shown in Figure 2.

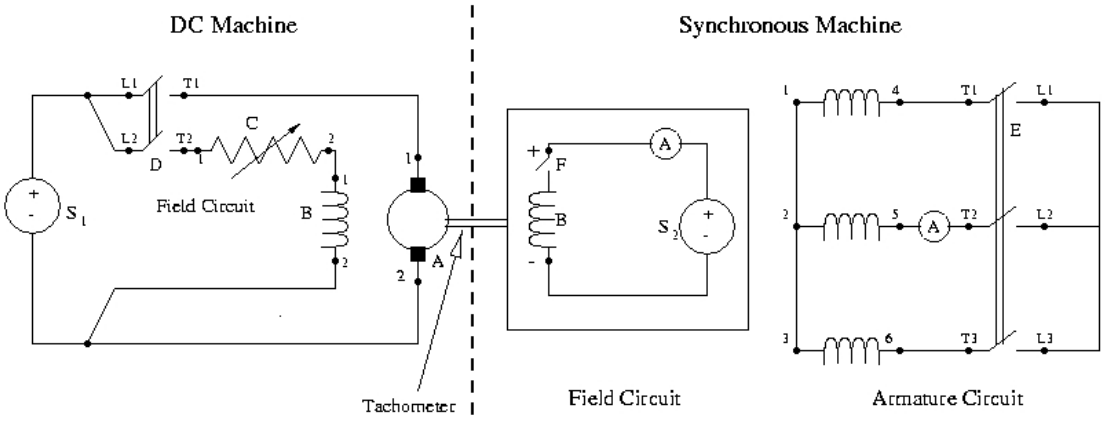

Figure 2

2) Repeat steps 3, 4 and 5 of Part A.
3) Apply field voltage (S_2) to the synchronous machine by switching **F** to '**Syn. Run**' position (Right). Adjust S_2 to obtain approximately 120% of the rated armature current through the short circuit (rated armature current is 1.7 A, hence $I_{armature}$ = 1.7 $\times$1.2 = 2.04 A). Record the armature current $I_{armature}$ and the field current I_f, and tabulate the data points in Table 3.
4) Obtain six more data points for the short circuit armature current and field current by decreasing the field current I_f to 1 A, 0.9 A, 0.8 A, 0.72 A, 0.6 A, 0.54 A. Record $I_{armature}$, I_f and tabulate the data points in Table 2.1. Remember that changing the field current will change the speed. **Make sure that the speed is equal to 1800 rpm** before recording any values.

5) Adjust the speed to 1600 rpm and repeat 3 – 4 of Part B. Tabulate the values in Table 2.2.
6) Set the field voltage (S_2) of synchronous machine to zero and switch the voltage supply off. Stop the DC motor by first gradually reducing S_1 to zero and then switch 'D' to off and wait until the machine stops completely.

Part C: Armature measurements

1) Measure the armature winding resistance of the synchronous generator.

Part D: Load Test

1) Connect the synchronous generator as shown in Figure 1
2) Set the DC variable voltage source (S_2) to 0 and set the field rheostat 'C' of the DC motor at its maximum. Move switch F to 'Ind. Start' position (left) so that the synchronous machine can be started as a motor.
3) Have the instructor check your machine and meter connections before proceeding.
4) Turn on switch 'D' and start the DC motor. Use the field rheostat 'C' to adjust the speed to 1800 rpm. Once the speed is set, move switch F to the 'Syn. Run' position (right).
5) Using the variable voltage source S_2, adjust the field current of the synchronous generator to obtain the rated terminal voltage. **Keep the field current and speed constant through the end of Step 7.**
6) Connect the load resistors (wye-connected) to the synchronous generator as shown in Figure 1.
7) Increase the resistive load in the order indicated in Table 1. Use Table 1 to record the magnitude of the terminal voltage ($|V_t|$) and the magnitude of the armature current ($|I_a|$) of the synchronous generator.
8) Set the field voltage of synchronous machine to zero and switch off the voltage supply. Stop the DC motor by switching 'D' off and waiting until the machine comes to a full stop.
9) Disconnect the load from the generator.

10) Use field rheostat 'C' to adjust the speed to 1800 rpm and adjust the field current to obtain rated terminal voltage. Repeat these adjustments several times until the speed is 1800 rpm and the terminal voltage is at its rated value. **Keep the terminal voltage and the speed of the synchronous generator constant through the end of Step 3.**

11) Set the resistive load to 600 Ω. This value will stay constant throughout this step. Then increase the reactive load by adding inductors in parallel, one at a time, in the order given in Table 2. Use Table 2 to record the armature current ($|I_a|$) and the field current (I_f) of the synchronous generator at each step.

12) Set the field voltage of synchronous machine to zero and switch off the voltage supply. Stop the DC motor by switching 'D' off and waiting until the machine comes to a full stop.

Optional, Ungraded Report

1. Plot on the same graph the open circuit armature voltage versus the field current when the speed is 1800 rpm and 1600 rpm. These are referred to as the open circuit characteristics (OCC).
2. Plot on the same graph the short circuit armature current versus the field current when the speed is 1800 rpm and 1600 rpm. These are referred to as the short circuit characteristics (SCC).
3. Using the plots from parts 1 and 2, plot the synchronous reactance versus field current when the speed is 1800 rpm. Note that the synchronous reactance is defined as the ratio of the open circuit terminal voltage (line-to-neutral) to the short circuit armature current corresponding to the same field current excitation.
4. Draw a tangent to the OCC (for 1800 rpm) at the origin. This straight line is referred to as the air gap line (AGL). Is the armature voltage zero at the origin (I_f=0)? Why or why not? Explain.
5. Calculate the saturated synchronous reactance by using the following definition:

$$X_s = \frac{V_r}{I_0}$$

where:

V_r = Rated armature voltage (line to neutral) .

I_0 = Armature current from the SCC corresponding to the value of I_f which will yield rated armature voltage on the OCC.

6. Calculate the unsaturated synchronous reactance by using the following definition:

$$X_u = \frac{V_{agl}}{I_0}$$

where:

V_{agl} = Line to neutral AGL voltage corresponding to the rated value of I_f (which gives the rated armature voltage at OCC).

I_0 = Armature current from the SCC corresponding to the rated value of I_f.

7. Draw and label the equivalent circuit.
8. Show that the per unit value of the saturated synchronous reactance can be calculated by using the following expression

$$X_s(p.u.) = \frac{I_{fi}}{I_{fv}}$$

where:

I_{fi} = Value of I_f corresponding to the rated armature current on the SCC.

I_{fv} = Value of I_f corresponding to rated armature voltage on the OCC

9. What is the relation between the rotor speed and open circuit armature voltage? Verify your answer by using experimental data. Does the relation remain the same for different values of field current? Explain why or why not.
10. What is the relation between the rotor speed and short circuit armature current? Does it remain the same for different field currents? Explain your answer.

Table 1 (Open Circuit Test, Speed = 1800 rpm)

V_{LL} (Volts)							
I_f (A)							

Table 2 (Open Circuit Test, Speed = 1600 rpm)

V_{LL} (Volts)							
I_f (A)							

Table 3 (Short Circuit Test, Speed = 1800 rpm)

$I_{armature}$ (A)						
I_f (A)						

Table 4 (Short Circuit Test, Speed = 1600 rpm)

$I_{armature}$ (A)						
I_f (A)						

11. Using the synchronous machine model developed in the beginning of the experiment, calculate the expected magnitudes of the terminal voltage ($|V_t|$) and then fill out the corresponding column in Table 1. Plot the calculated and the measured values of $|V_t|$ vs. $|I_a|$ on the same graph. Compare and discuss any discrepancies between the two plots.

12. Calculate the power angle δ for each $|I_a|$ using $\delta = \sin^{-1}\left[\frac{|I_a| \cdot X_s}{|E_f|}\right]$. Then calculate the three-phase real power P dissipated by the load for the same $|I_a|$ values. Fill in the corresponding columns in Table 5. Plot the calculated P versus δ values and comment on the shape of the curve.

13. Calculate the power factor angle θ of the load using the below equation and fill in the θ column of Table 6

$\theta = -\tan^{-1}\left[\frac{B}{G}\right]$, where G + jB is the admittance of the per phase load.

14. Calculate the field excitation voltage phasor (magnitude and angle) using the below equation assuming that the angle of the terminal voltage is zero. Fill in the $|E_f|$ and δ columns in Table 6.

$$|E_f|\angle\delta = |V_t|\angle 0 + |I_a|\angle -\theta \cdot (R_a + jX_s)$$

15. Draw the phasors $|V_t|\angle 0, |E_f|\angle\delta, |I_a|\angle -\theta$ for all loading conditions on the same complex plane. Note that for all conditions the terminal voltage will remain the reference phasor along the real axis with a constant magnitude.
16. Calculate the three-phase reactive power output, Q, of the synchronous

generator and fill in the Q column in Table 6. Plot Q versus I_f; comment on the results.

Table 5: I_f = constant, f = 60 Hz

R (Ω) Resistive Load			Recorded Values		Calculated Values		
150	300	600	$\lvert V_t \rvert$ (volts) line-to neutral	$\lvert I_a \rvert$ (amps)	$\lvert V_t \rvert$ (volts)	δ (°)	P (W)
0	0	0					
0	0	1					
0	1	0					
1	0	1					
1	1	0					
1	1	1					

Table 6: R = 600 Ω, V_t = 120 V (line-to neutral), f = 60 Hz

L (H) Inductive Load			Recorded Values		Calculated Values			
0.4	0.8	1.6	$\lvert I_a \rvert$ (amps)	I_f (amps)	δ (°)	$\lvert E_f \rvert$ (volts)	*Q*, (var)	θ (°)
0	0	1						
0	1	0						
1	0	0						
1	0	1						
1	1	0						