University of Virginia
Engineering Laboratories
ECE 3251

Lab Day & Time Friday 9-11am

EXPERIMENT NUMBER #10

TITLE Synchronous Machine

LAB PARTNER(S) NAME Sam Holliday

LAB PARTNER(S) NAME Izzy LaRocco

LAB PARTNER(S) NAME Henry Toth

LAB BENCH USED 4

DATE PERFORMED: 4/10/2026

DATE SUBMITTED: 4/17/2026

PLEDGE

(1) The data presented here were collected in the laboratory by our group members. We have neither added to nor altered that data.
(2) While we may have discussed this lab with others, the work and conclusions contained herein are those of our team.

Signed

Isidore LaRocco
Samuel Holliday
Henry Toth

Team Member Contribution

Sam Holliday: Performed adjustments on the lab setup according to the procedure and wrote python script to calculate Xs (in-lab). Wrote Introduction Section (write-up).
Izzy LaRocco: Set up spreadsheet for calculations, recorded data (in-lab). Drafted Procedures and Conclusion sections, contributed to Results section (write-up).
Henry Toth: Formatted the initial steps of the spreadsheet and recorded measurements into spreadsheet(in-lab). Drafted Conclusion section and revised the Results section (write-up).

Introduction

The purpose of this lab is to investigate the operation of a synchronous machine connected to the grid. In this experiment, the machine is first characterized by its intrinsic armature resistance. Then, the relationship between the field current and phase voltage is investigated as a DC machine is used as its prime mover. After finding the field current that makes the phase voltage of the synchronous machine match the phase voltage of the grid, the synchronous machine is connected to the grid. To finish the characterization of the machine, the per-phase reactance of the synchronous machine is iteratively calculated using measured voltage, current, real power, and reactive power while the torque is close to zero. Finally, the lab qualitatively investigates how the power absorbed turns into power supplied with varied field current.

Procedure

Safety Procedures

- Ensured proper attire was worn to avoid any dangerous situation with the rotating shaft.
- Ensured all cables used were of minimal length to avoid contact with the rotating shaft.
- Ensure cables are routed in a way that reaching over or across the rotating shaft is not required when adjusting the variacs.

Field Resistance, Armature Resistance, and Supply Voltage

1. Configured bench for measurements.
    a. Connected the synchronous machine control cable to the Data Acquisition Panel.
    b. Configured banana cables as applicable to accommodate following the measurements.
2. Measured resistances of field and armature.
    a. Used the Fluke Digital Multimeter (DMM) to measure the field resistance.
    b. Used the Fluke DMM to measure individual resistance of each phase of the synchronous machine armature.
3. Measured bench input voltages.
    a. Used the Fluke DMM to measure voltage of each phase on Bench Power Panel input terminals.

Synchronous Machine Configuration

4. Set up the synchronous machine as a generator in wye configuration.
    a. Connected the positive stator terminals to the negative AC current terminals.
    b. Arranged the negative stator terminals in parallel and connected them to the negative AC high voltage terminals.

    c. Jumpered the positive AC current and positive AC high voltage terminals to their respective phases.
    d. Connected the left DC Power Panel in series to the field terminals and the Fluke DMM.
5. Set up the DC machine as a motor.
    a. Connected the DC machine to the right DC Power Panel variac.
6. Referenced the torque reading to zero in the LabVIEW "Speed and Torque" tab.

Magnetization Curve Measurements

7. Recorded field current and armature voltage for magnetization curve characterization.
    a. Adjusted DC motor variac to 1795-1805 RPM.
    b. Recorded field current from the Fluke DMM.
    c. Recorded armature voltages from LabVIEW.
    d. Verified expected shape of curve using Excel plot.
8. Recorded field current required to create output voltages within 1V of the input voltages.
9. Recorded field current required to create output voltages at 75% of Step 8 values.
10. Slowly returned variacs to 0%, starting with generator.
11. Removed power.

Synchronization with Grid

12. Configured synchronous machine with synchronizing lamps box.
    a. Connected positive AC current terminals from Data Acquisition Panel to one side of box.
    b. Connected top AC terminals from Bench Power panel to other side of box.
    c. Jumpered lower phase terminals to respective upper phase terminals on either side of box.
13. Synchronized the synchronous machine with the grid.
    a. Adjusted DC motor variac to "near" 1800 rpm.
    b. Adjusted synchronous generator field current to value found in Step 8 to match phase voltages.
    c. Reversed DC motor terminals after finding that synchronizing lamps were not glowing together.
    d. Connected the switch when all lights were simultaneously off, indicating no voltage drop across the lamps.

Real Power Test

14. Verified output power.
    a. Recorded real power from all three phases on "3 Phase Power" tab on LabVIEW.
    b. Verified real power was small, approximately 2-3W.
15. Increased torque to generator.
    a. Slowly adjusted DC machine variac until reading approximately 60W per phase on LabVIEW.
    b. Verified reactive power remained constant while increasing DC machine variac.
16. Verified input power.
    a. Recorded real power from "Speed and Torque" tab on LabVIEW.
17. Calculated efficiency.

Reactive Power Test

18. Reduced field current to Step 9 value using synchronous machine variac.
19. Recorded data from leading power configuration.
    a. Recorded armature voltage, field current, real power, and reactive power from all three phases on “3 Phase Power” tab on LabVIEW.
    b. Averaged measurements across the three phases.
20. Used given armature voltage definition to calculate phase angle of the current.

Field Current Test

21. Observed effects of changing field current all phases.
    c. Increased field current from 0.3A to 0.8A using synchronous machine variac.
    d. Observed real power and reactive power on “3 Phase Power” tab on LabVIEW.
    e. Identified leading and lagging behavior with variation of field current.
    f. Recorded observations and screenshots of extremes and transition points.
22. Observed effects of changing field current on phase A.
    g. Increased field current from 0.3A to 0.8A using synchronous machine variac.
    h. Observed phase of current on “Basic 1P Power” tab on LabVIEW.
    i. Identified leading and lagging behavior with variation of field current.
    j. Identified harmonic distortion behavior with variation of field current.
    k. Recorded observations and screenshots of extremes and transition points.

Desynchronization with Grid

23. Adjusted torque to zero using DC machine variac.
24. Adjusted synchronous machine phase voltage to match bench power phase voltage using synchronous machine variac.
25. Disconnected the switch on the synchronizing lamps box.
26. Slowly returned variacs to 0%, starting with generator.
27. Removed power.

Results

Method of Calculation

This section details the calculations used to find the synchronous machine operational characteristics from resistance, voltage, current, and power measurements.

Average Armature Resistance and Supply Voltage

The armature resistance and bench supply voltage were averaged to establish baseline values for per-phase analysis:

$$R_{avg} = \frac{R_A + R_B + R_C}{3}$$

$$V_{phase\ avg} = \frac{V_A + V_B + V_C}{3}$$

Armature Voltage (Open Circuit Test)

The armature voltage was measured in the open circuit test. The definition of armature voltage for a synchronous machine was found as:

$$E_a = V_{phase}.$$

Generator Efficiency
The efficiency of the synchronous machine configured as a generator was calculated as:

$$\eta = \frac{P_{dev}}{P_{electrical}} * 100\% = \frac{P_{out}}{P_{in}} * 100\%$$

Synchronous Reactance
The synchronous reactance was solved using an iterative program using the per-phase vector equation:

$$E_a\angle\delta = V_\phi\angle 0° + R_a I_a\angle\theta + jX_s I_a\angle\theta$$
$$X_s = \frac{1}{jX_s\angle\theta}[E_a\angle\delta - V_\phi\angle 0° - R_a I_a\angle\theta].$$

Initial Parameters – Resistance and Supply Voltage

Parameter	Phase A	Phase B	Phase C	Average Per-Phase
Armature Resistance (Ω)	11.69	11.73	11.77	11.73
Supply Voltage (V)	125.5	125.9	124.9	124.4

Table 1. Tabulated per-phase and average results of the synchronous machine armature resistances and bench supply voltages.

The field resistance was measured as 132Ω. The 75% value of the average phase voltage was found to be 94.08V.

Magnetization Curve Measurements

Field Current (A)	Phase A (V)	Phase B (V)	Phase C (V)	Average Phase Voltage (V)
0.1	31.1	31.2	31.2	31.17
0.2	59.1	59.2	59.1	59.13
0.3	82.2	82.2	82.2	82.2
0.4	100.6	100.6	100.5	100.57
0.5	113.9	114.1	113.9	113.97
0.6	123	123.5	123.4	123.3
0.7	130.4	130.6	130.3	130.43
0.8	136.2	137	136.3	136.5

Table 2. Tabulated results of the phase voltages from varying the field current through the synchronous machine.

The current required to match synchronous machine voltages to the previously measured supply voltages was found to be 0.619A. The current required to match 75% of the supply voltage was found to be 0.361A.

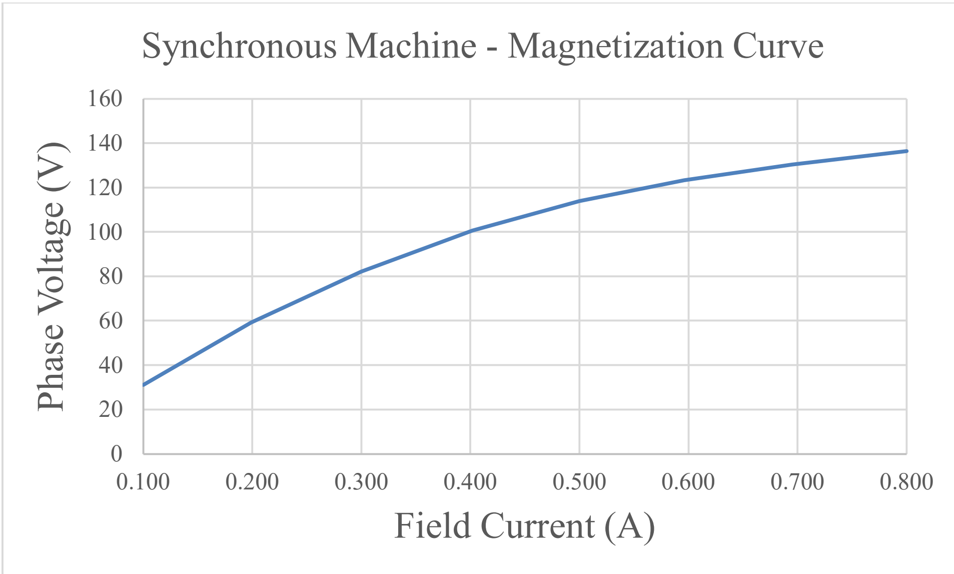

Figure 1. The magnetization curve of the synchronous machine with field current plotted against phase voltage.

Synchronized Power Test – 180W

Parameter	Phase A	Phase B	Phase C	Total
Real Power (W)	-59	-60	-60	-179

Parameter	Value
Mechanical Power (W)	-248
Electrical Power (W)	-179
Efficiency	72.18%

Table 3. Tabulated results of the real power input and output to the synchronous machine after synchronization with the grid.

Per-Phase Model Parameters

Variable	Parameter	Value
E_a	Armature Voltage	95.48 V
$V_{\phi\ avg}$	Average Phase Voltage	127.3 V
$I_{a\ avg}$	Average Armature Current	0.92 A
$R_{a\ avg}$	Average Armature Resistance	11.73 Ω
X_s	Synchronous Reactance	57.01 Ω
θ	Phase Angle	-58.64°
δ	Torque Angle	22.40°

Table 4. Tabulated per-phase model parameters of the synchronous machine found during synchronization with the grid.

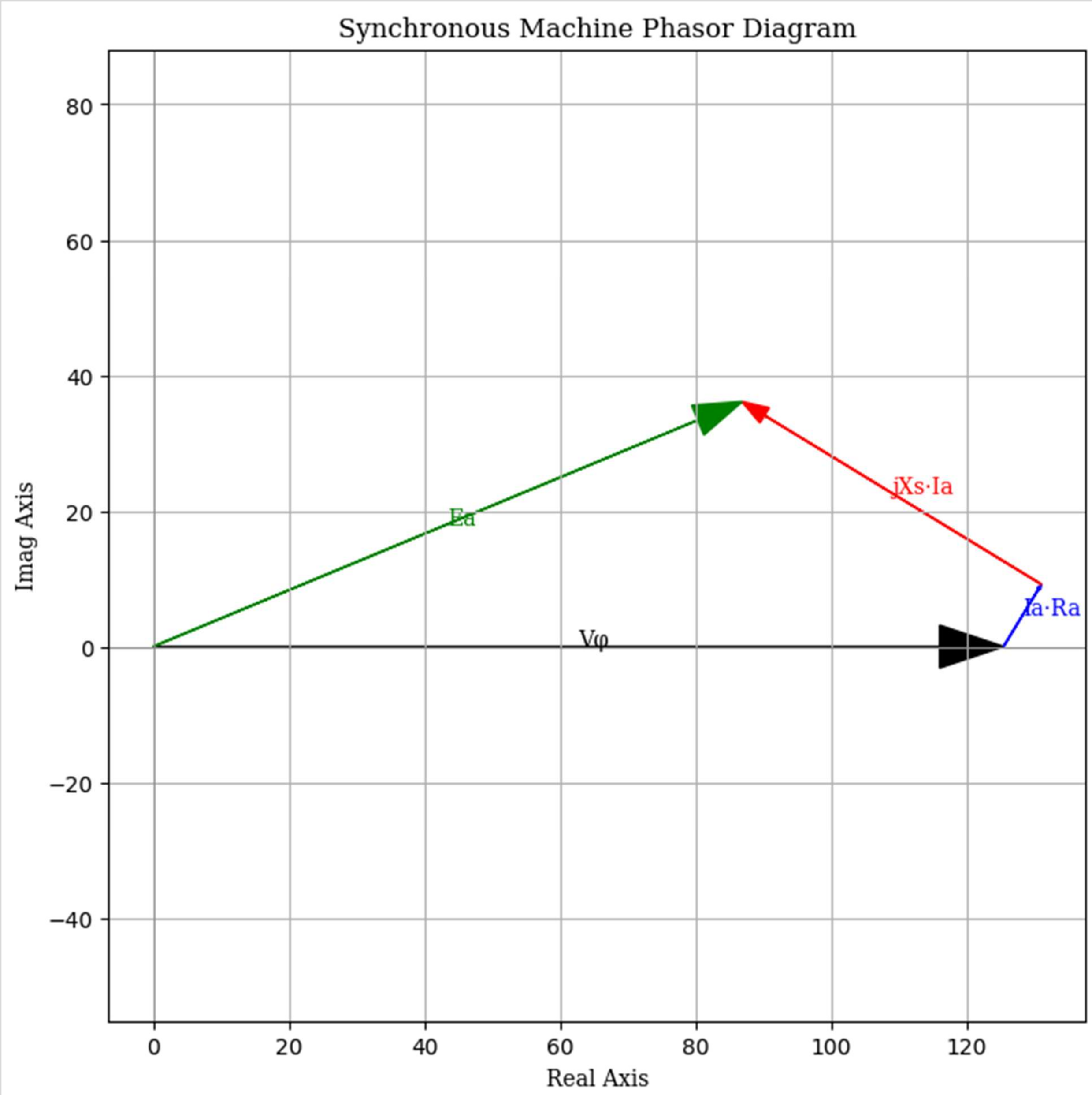

Figure 2. The phasor diagram for the synchronous machine equation.

Field Current Test – Three Phase Observations

When the field current is increased from 0.3A to 0.8A, the real power becomes even more negative. The synchronous machine is generating more power and supplying it to the grid. Additionally, the reactive power goes down significantly.

The reactive power is leading when the armature voltage is greater than the phase voltage. The reactive power is lagging when the armature voltage is less than the phase voltage. These are both set using the field current. The "tipping point" between leading and lagging occurred at approximately 0.66A.

Field Current Test – Single Phase Observations
The current waveform shifts from leading to lagging above the identified 0.66A field current threshold. Perfectly negative power was found at 0.71A field current, indicating real power being generated with no reactive power. Power factor became more negative as the field current increased.

We observed increasing fifth harmonic distortion with increasing field current.

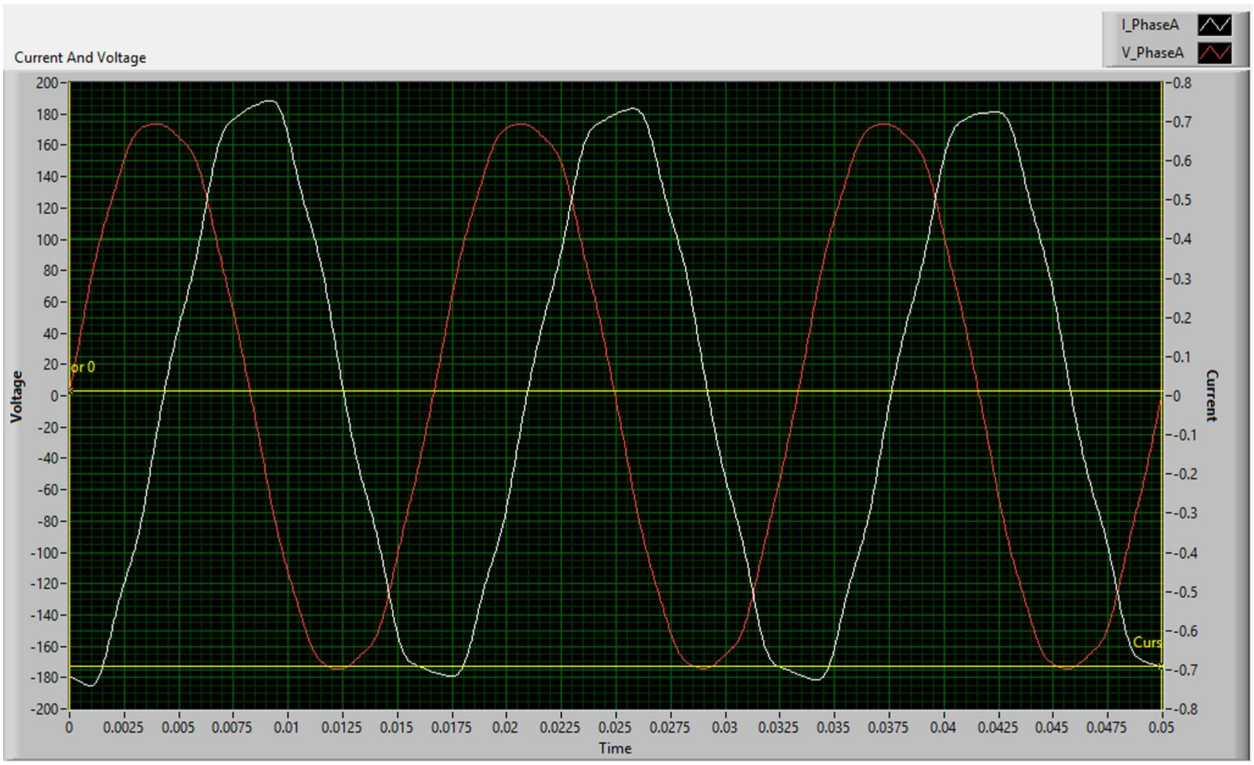

Figure 3. Voltage and current curves for a 0.3A field current demonstrating a lagging current.

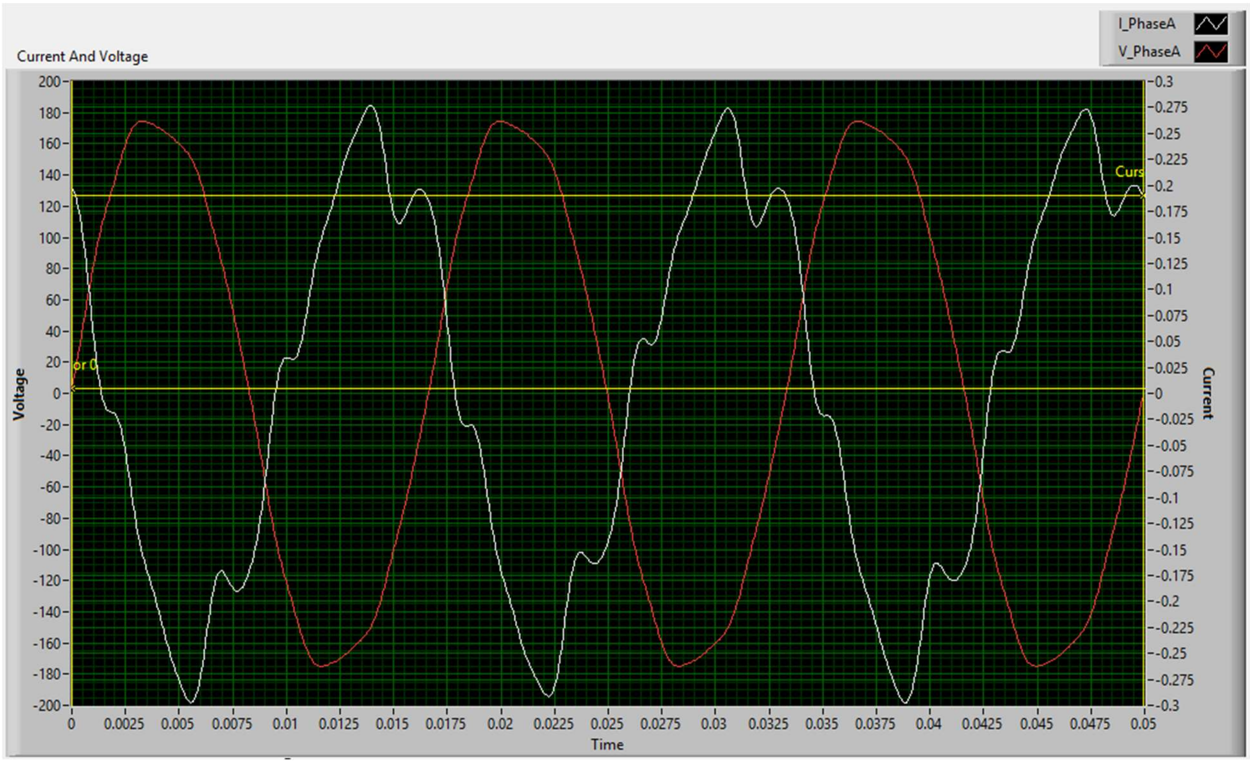

Figure 4. Voltage and current curves for a 0.8A field current demonstrating a leading current.

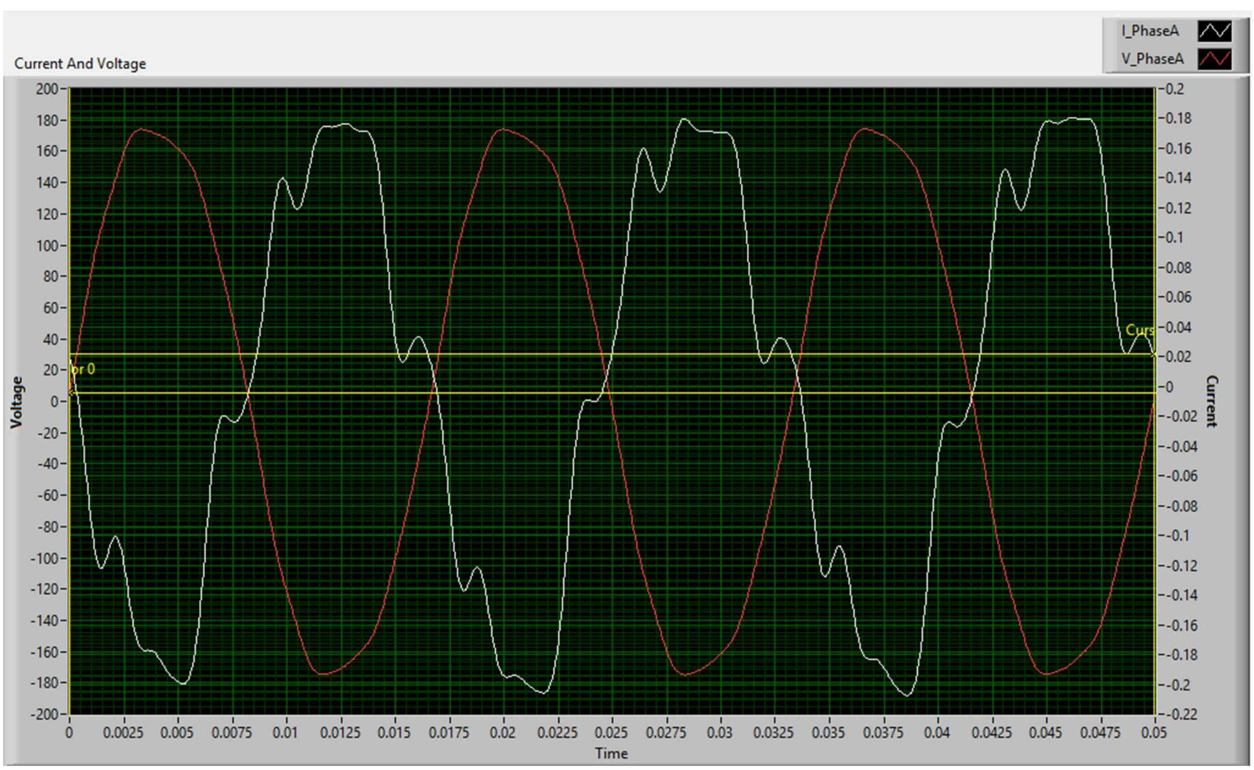

Figure 5. Voltage and Current curves for 0.71A field current, the 'tipping point' demonstrating a perfectly inverted current with respect to voltage.

Conclusion

The objective of this experiment was to characterize the performance of a synchronous machine through variation of input parameters and to observe the operational behavior of a synchronous machine while synchronized with the grid.

The magnetization curve was made with the motor at the upper limit of the acceptable synchronous speed range, 1805 RPM. The exact field currents were used for plotting against average phase voltage. The magnetic saturation of the iron core is difficult to pinpoint. However, at approximately 0.4A the curve starts to plateau. The synchronous machine operates in the linear region from approximately 0.1A to 0.4A, and in the saturated region above 0.4A. The saturation of the iron core is the same effect observed in previous labs, the flux density meets its maximum concentration. This increased flux density results in non-linear behavior of the generator.

The synchronization with the grid allowed us to observe power generation and to modify power factor of the synchronous machine. Real power was observed near 180W, we were able to establish 179W of real power generated with phase A at 59W, phase B at 60W, and phase C at 60W. The efficiency in this 180W condition was 72.18%. This efficiency calculation only considers mechanical power into the generator and electrical output power. We are aware of losses such as field power, friction, windage, and heat loss in the armature windings, but did not take these into account for simplicity.

During the three phase field current test, we found that the unity power factor occurred at approximately 0.66A. At this field current, the armature voltage is adjust to be exactly equal to the magnitude of the phase voltage. This results in an output of only real power with a power factor of 1. At this point, the synchronous machine is in sync with the grid. The armature resistance may have caused some error in field current, requiring us to deviate upward from the previously identified field current required to get reactive power.

During the field current test on phase A, we found that the unity power factor occurred at slightly higher than for the three phase test at 0.71A. At this point, the synchronous machine is in sync with the grid. Our observation of fifth harmonic distortion appeared to contradict the lab document instructions, which advise looking for third harmonic distortion. This fifth harmonic distortion is caused by operation of the synchronous machine with core saturation.

We found that the synchronous machine acted as a synchronous capacitor when the field current was less than approximately 0.70A. In this region, the machine was under-excited and absorbing reactive power from the grid. The power factor observed here was leading. Conversely, we found that the synchronous machine acted as a synchronous inductor when the field current was greater than approximately 0.70A. In this, region the machine was over-excited, adding reactive power to the grid, and the power factor was lagging.