Lab 14: 3-phase alternator.

Objective: to obtain the no-load saturation curve of the alternator; to determine the voltage regulation characteristic of the alternator with resistive, capacitive, and inductive loading; to observe the effect of unbalanced load.

Equipment: Power Supply, DAI, Synchronous motor/generator module (8241), Squirrel cage induction motor (8221), DC motor (8211), Variable resistance (8311), Variable inductance (8321), Variable capacitance module (8331), Tachometer, Timing belt.

Theory:

The squirrel cage motor will be used in this exercise to drive the synchronous generator. Since no laboratory experiments were performed on a motor of this type, the following overview may be useful.

The simplest and most widely-used rotor for induction motors is the so-called squirrel cage rotor, from which the squirrel cage induction motor gets its name. The squirrel cage rotor consists of a laminated iron core which is slotted lengthwise around its periphery. Solid bars of copper or aluminum are tightly pressed or embedded into the rotor slots. At both ends of the rotor, short-circuiting rings are welded or brazed to the bars to make a solid structure. The short-circuited bars, because their resistance is much less than the core, do not have to be specially insulated from the core. In some rotors the bars and end rings are cast as a single integral structure for placement on the core. The short-circuiting elements actually form shorted turns that have high currents induced in them by the stator field flux.

Compared to the intricately wound and arranged wound rotor or the armature of the DC motor, the squirrel cage rotor is relatively simple. It is easy to manufacture and is essentially troublefree in actual service.

In an assembled squirrel cage induction motor, the periphery of the rotor is separated from the stator by a very small air gap. The width of this air gap, in fact, is as small as mechanical clearance needs will permit. This insures that the strongest possible electromagnetic induction action will take place.

When power is applied to the stator of a practical induction motor, a rotating magnetic field is created by any one of the means you learned about. As the field begins to revolve, its flux lines cut the shorted turns embedded around the surface of the squirrel cage rotor and generate voltages in them by electromagnetic induction. Because these turns are short-circuits with very low resistance, the induced voltages cause high currents to circulate in the rotor bars. The circulating rotor currents then produce their own strong magnetic fields. These local rotor flux fields produce their own magnetic poles, which are attracted to the rotating field. Thus, the rotor revolves with the main field.

The starting torque of the basic squirrel cage induction motor is low, because at rest the rotor has a relatively large inductive reactance ($X_L$) with respect to its resistance ($R$). Under these conditions we would expect the rotor current to lag rotor voltage by 90 degrees. We thus say that the power factor in the circuit is low. This means that the motor is inefficient as a load and cannot derive really useful energy for its operation from the power source.
Despite the inefficiency, torque is developed and the motor begins to turn. As it starts turning, the difference in speed between rotor and rotating field, or slip, goes from a maximum of 100 percent to some intermediate value, say 50 percent. As the slip decreases in this manner, the frequency of the voltages induced in the rotor decreases, because the rotating field cuts conductors at a decreased rate; this, in turn, causes the overall inductive reactance in the circuit to decrease. As inductive reactance decreases, the power factor begins to increase. This improvement is reflected as an increase in torque and a subsequent increase in speed.

When the slip drops to some value between 2 and 10 percent, the motor speed stabilizes. This stabilization occurs because every tendency for the motor speed to increase to where slip will drop below 2 percent is naturally offset by the fact that, as the rotor approaches within 2 percent of the synchronous speed, the effects of reduced induction overcome the previous tendency to increase torque as the motor is speeded up from start. Thus, the motor exhibits an automatic speed control characteristic similar to that of the DC shunt motor.

The terms alternating current generator, synchronous generator, synchronous alternator, and alternator are commonly used interchangeably in engineering literature. Because synchronous generators are so much more commonly used than induction generators, the term alternator, as often used, and as used here, applies only to synchronous generators.

Alternators are, by far, the most important source of electric energy. Alternators generate an AC voltage whose frequency depends entirely upon the speed of rotation. The generated voltage value depends upon the speed, the DC field excitation and the power factor of the load.

As the DC field excitation of an alternator is increased, its speed being held constant, the magnetic flux, and hence, the output voltage, will also increase in direct proportion to the current. However, with progressive increases in DC field current, the flux will eventually reach a high enough value to saturate the iron in the alternator.

Saturation in the iron means that there will be a smaller increase in flux for a given increase in DC field current. Because the generated voltage is directly related to the magnetic flux intensity, it can be used as a measure of the degree of saturation.

The three phases of the alternator are mechanically spaced at equal intervals from each other, and therefore, the respective generated voltages are not in phase, but are displaced from each other by 120 electrical degrees.

When an alternator delivering full rated output voltage is suddenly subjected to a short-circuit, very large currents will initially flow. However, these large short-circuit currents drop off rapidly to safe values if the short-circuit is maintained.

The output voltage of an alternator depends essentially upon the total flux in the air-gap. At no load, this flux is established and determined exclusively by the DC field excitation.

Under load, however, the air-gap flux is determined by the ampere-turns of the rotor and the ampere-turns of the stator. The latter may aid or oppose the MMF (magnetomotive force) of the rotor depending upon the power factor of the load. Leading power factors assist the rotor, and lagging power factors oppose it.
Because the stator MMF has such an important effect upon the magnetic flux, the voltage regulation of alternators is quite poor, and the dc field current must continuously be adjusted to keep the voltage constant under variable load conditions.

If one phase of a 3-phase alternator is heavily loaded, its voltage will decrease due to the IR and $LX_L$ drops in the stator winding. This voltage drop cannot be compensated by modifying the dc field current because the voltages of the other two phases will also be changed. Therefore, it is essential that 3-phase alternators do not have loads that are badly unbalanced.

The **alternator regulation** can be calculated as

$$\text{regulation} = \frac{E_{nl} - E_{fl}}{E_{fl}} \times 100\% \quad (14-1)$$

where $E_{nl}$ and $E_{fl}$ are the no-load and full-load voltages.

**Experiment:**

1) Connect the circuit shown in Figure 14-1. The speed of the squirrel cage motor will be assumed constant through the experiment. In the Metering window, enable three AC voltmeters and one DC ammeter.

Couple the squirrel cage motor to the alternator with the timing belt. Set the alternator field rheostat at its utmost clockwise position for zero resistance. Make sure that the PS control knob is at its zero position.
2) Turn ON the PS. The motor should be running. Turn ON the switch on the synchronous motor/generator. Measure and record in a Data table the values of the excitation current $I_1$ and the voltages induced on the three winding $E_1$, $E_2$, and $E_3$ for the excitation currents from 0 to 0.9 A with the increment of 0.1 A.

3) Set the DC excitation current to approximately 0.2 A. Start the Oscilloscope and observe three voltages generated by the alternator. You may use the following channel setting for a better representation: 50 V/div, 10 mS/div. Import the scope data to a txt file.

4) Start the Phasor analyzer and observe the three phasors corresponding to the three output voltages. Print the phasor analyzer to a pdf-file using the PDF Creator.

5) Adjust the DC excitation until the generated voltages equal approximately to 208 V. Record the values of the excitation current and the three voltages generated in your data table. Turn OFF the PS without touching the voltage adjustment control. Reconnect your voltmeters to measure the voltages across each of the three windings and turn ON the PS. Measure and record in the Data table the values of the DC excitation current and the three voltages generated. Return the voltage to zero and turn OFF the PS. Disassemble your circuit and uncouple the motor and the generator.

6) Replace the squirrel cage motor by the DC motor and construct the circuit shown in Figure 14-2. Note that the DC motor is connected to the fixed DC source while a variable DC is applied to the alternator rotor.

![Figure 14-2](image-url)
Couple the DC motor to the alternator with the timing belt. Connect the tachometer to the BNC terminal on the DC motor. Set the DC motor field rheostat at its utmost counterclockwise position for maximum resistance. Set the load resistance of each section to 300 Ω.

7) Turn ON the PS and adjust the DC motor rheostat for a motor speed of 1800 rpm. *Note: this speed must be kept constant for the remainder of this experiment.* Close the switch S on the synchronous motor and adjust the DC excitation until the output voltage of the alternator is approximately 120 V. Measure and record in a new Data table the values for full-load currents $I_1$ and $I_2$ and the output voltage. Open the Phasor analyzer window and assess the phase angle between the alternator voltage $E_1$ and the load current $I_1$. Print the result to a pdf-file. Turn OFF all three switches on the resistance module for no load on the alternator. Measure and record in the Data table the values for full-load currents $I_1$ and $I_2$ and the output voltage. Remember to readjust the motor speed to 1800 rpm if necessary. Return the voltage to zero and turn OFF the PS.

8) Replace the resistive load by the inductive load. Set the load reactance of each section to 300 Ω. Turn ON the PS and adjust the DC motor rheostat for a motor speed of 1800 rpm. Adjust the DC excitation until the output voltage of the alternator is approximately 120 V. Measure and record in your Data table the values for full-load currents $I_1$ and $I_2$ and the output voltage. Evaluate (by means of the Phasor analyzer) the phase angle between the alternator voltage $E_1$ and the load current $I_1$. Print the result to a pdf-file. Turn OFF all three switches on the resistance module for no load on the alternator. Measure and record in the Data table the values for full-load currents $I_1$ and $I_2$ and the output voltage. Remember to readjust the motor speed to 1800 rpm if necessary. Return the voltage to zero and turn OFF the PS.

9) Replace the inductive load by the capacitive load. Set the load reactance of each section to 300 Ω. Turn ON the PS and adjust the DC motor rheostat for a motor speed of 1800 rpm. Adjust the DC excitation until the output voltage of the alternator is approximately 120 V. Measure and record in your Data table the values for full-load currents $I_1$ and $I_2$ and the output voltage. Evaluate (by means of the Phasor analyzer) the phase angle between the alternator voltage $E_1$ and the load current $I_1$. Print the result to a pdf-file. Turn OFF all three switches on the resistance module for no load on the alternator. Measure and record in the Data table the values for full-load currents $I_1$ and $I_2$ and the output voltage. Remember to readjust the motor speed to 1800 rpm if necessary. Return the voltage to zero and turn OFF the PS.

10) Construct the circuit shown in Figure 14-3. Note that only one of the alternator phases has a load.
Turn ON the PS and adjust the DC motor rheostat for a motor speed of 1800 rpm. Adjust the DC excitation until the voltage across the load is approximately 208 V. Measure and record the three alternator output voltages.

11) Set up one of the programmable meters to read the frequency of voltage \( E_1 \). With the voltage across the load being approximately 208 V, measure and record the motor speed (it should be close to 1800 rpm). Next, by adjusting the field rheostat on the DC motor, adjust the motor speed to 1775, 1750, 1725, and 1700 rpm while measuring and recording the voltage \( E_1 \) and its frequency. Record these values (speed, voltage and frequency) into a new data table.

**In your report:**

1) Using Matlab and the data collected in Part 2, calculate and plot the average output voltage of the alternator as a function of DC excitation current. Does this graph represent a linear dependence? Discuss possible reasons for non-linearity.

2) Explain why an AC voltage is generated in the absence of DC excitation?

3) Load to Matlab the oscilloscope data you collected in Part 3. On the same axes, plot the three output voltages as function of time (the plot should look similar to the oscilloscope screen seen in the lab). Make your graphs distinguishable. Judging from these plots, what do you conclude about the phase difference between the three generated voltages?
4) Include in your report the screenshot for the Phasor analyzer you printed to a pdf-file in Part 4. Does this result support your previous conclusion regarding the phase difference between the three generated voltages?

5) Report and compare the results of two measurements you took in Part 5. Was the DC excitation current approximately the same for both measurements? Do the measured voltages correspond to the ones coming from a normal 3-phase supply?

6) For the data collected in Part 7, calculate and report the alternator regulation with resistive loading. What is the phase angle between the voltage across the alternator winding and the current flowing through the load? Use the Phasor plot you saved in Part 7 to support your answer.

7) For the data collected in Part 8, calculate and report the alternator regulation with inductive loading. What is the phase angle between the voltage across the alternator winding and the current flowing through the load? Use the Phasor plot you saved in Part 8 to support your answer.

8) For the data collected in Part 8, calculate and report the alternator regulation with capacitive loading. What is the phase angle between the voltage across the alternator winding and the current flowing through the load? Use the Phasor plot you saved in Part 8 to support your answer.

9) Propose an explanation to the phenomenon you observed while changing types of alternator load. Based on your observations, would it be dangerous to connect an alternator to a long transmission line if the line acts like a capacitor (i.e., has a capacitive reactance)? Explain.

10) Report the three alternator output voltages you have recorded in Part 10 for a single-phase load. What is your conclusion regarding unequal loading of alternators?

11) Load the data you have recorded in Part 11. Plot the dependence of the generated voltage as a function of the prime mover’s speed. On the separate axes, plot the dependence of the generated voltage’s frequency as a function of the prime mover’s speed. Comment on the resulting graphs.