PART IB EXPERIMENTAL ENGINEERING

SUBJECT: ELECTRICAL ENGINEERING EXPERIMENT E2 (SHORT)

LOCATION: ELECTRICAL AND INFORMATION ENGINEERING TEACHING LABORATORY

SYNCHRONOUS MACHINE

1 OBJECTIVES

1. To perform open-circuit and short-circuit tests on standard three-phase synchronous machine.

2. To obtain values for the equivalent-circuit parameters of the machine.

3. To synchronise the machine to the three-phase supply at constant voltage.

4. To observe and record the power flow by control of shaft torque and rotor excitation.

5. To verify the standard equivalent-circuit of the machine.

2 SAFETY

For obvious reasons, the machines used in a student laboratory are small and well protected. You are most unlikely to injure yourself or damage the equipment, but nevertheless you should exercise care. If you get clothing or your hair entangled in the shaft, the results will be very unpleasant. You should also make quite certain that you have turned the variable-voltage supply to zero before switching it on. Never attempt to stop a rotating shaft manually.

1 Introduction

The synchronous machine is the most widely used type of generator, providing most of the electrical energy available from the national grid. The stator has a standard three-phase ac winding mounted in it and the rotor (the rotating member) has a dc winding that is connected to an external dc supply. For normal generator operation, the synchronous machine will be connected mechanically to a drive system (eg steam or gas turbine) with the stator winding connected to the grid supply via a synchronising switch – this is a procedure which you will also perform in the laboratory. Once the machine has been connected electrically to the grid supply, the rotor speed remains **constant** and is determined simply by the supply frequency (50 Hz) and the number of poles in the generator. The drive system will then be used to attempt to increase the speed of the generator by increasing the mechanical power into the shaft. The generator speed cannot change so the mechanical power is converted to electrical power by the generator and fed out to the mains supply. Control of the rotor dc excitation allows the power factor at which the power is delivered to the grid to be varied. In simplistic terms, the generator can be regarded as having two basic controls: the drive system controlling the **total amount of power generated**; and the rotor dc excitation controlling the **output power factor**. Fig. 1 shows a schematic of the power flow during normal generator operation.

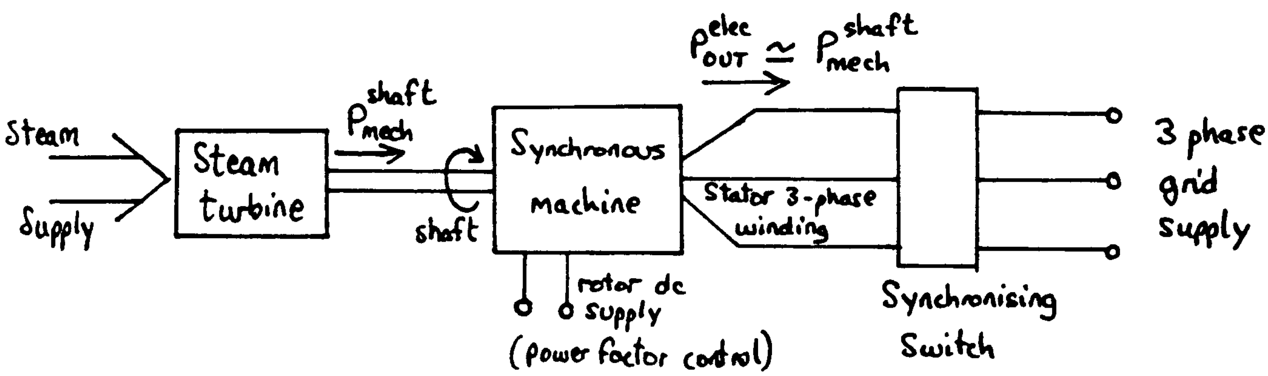

Figure 1

In this short experiment, you will carry out an *open-circuit test* and a *short-circuit test* to determine the equivalent-circuit parameters of a small synchronous machine. You will then synchronise the machine to the laboratory supply and perform load tests at two different rotor excitation conditions, and compare your predictions with the measurements carried out on the generator. The purpose of this is simply to demonstrate to you that the simple synchronous machine equivalent-circuit that you will develop in your lecture course is a reasonably accurate model of real machine behaviour.

2 Equipment

The synchronous machine to be tested is mechanically coupled to a dc motor. The dc motor is used to drive the generator round during the open-circuit and short-circuit tests and to get it up to synchronous speed for synchronising the generator in the load tests. Once the generator has been synchronised to the supply, the dc machine acts as the motor providing the input mechanical power. The dc motor is fed from an electronic dc supply that is mounted in the panel. The speed control potentiometer is also mounted in the panel and the procedure for starting is as follows:

1. Ensure that the three-phase contactor is OPEN.
2. Set the multi-turn speed potentiometer to the zero position (fully anti-clockwise).
3. Switch on the supply to the control unit.
4. Control the speed by rotating the potentiometer and monitoring the speed on the digital meter in the panel.

The synchronous generator is rated as follows:

Number of pole	=	4
Full load power	=	4 kW
Rated stator voltage	=	220 Volts
Rated power factor	=	0.8
Frequency	=	50 Hz
Stator winding connection	=	DELTA

The stator windings are brought out to three terminals on your panel. The rotor dc field winding is excited using a single-phase Variac via a bridge rectifier. The laboratory supply is connected to a three-phase Variac so that it can be adjusted to match the generator stator voltage. The three-phase Variac supply is also brought out to three terminals on the panel.

3 Preliminary Tasks

From the full load power and rated power factor, calculate the rated PHASE current of the generator. (Remember, the stator is DELTA connected.)

I = ... Amps

What is the corresponding LINE current?

I = ... Amps

The field winding on the synchronous machine has a reverse-connected diode (see Fig. 2a). Why is the diode necessary?

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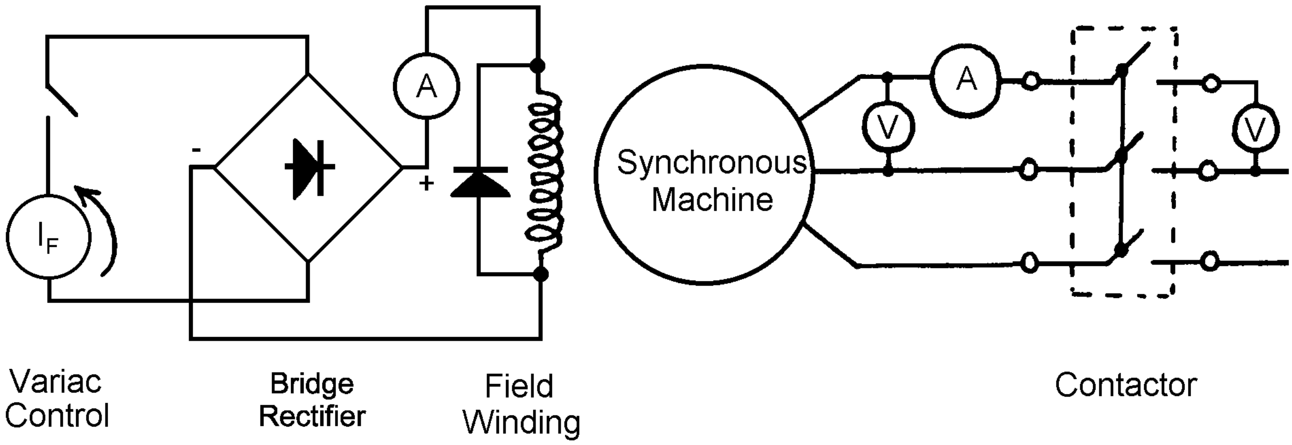
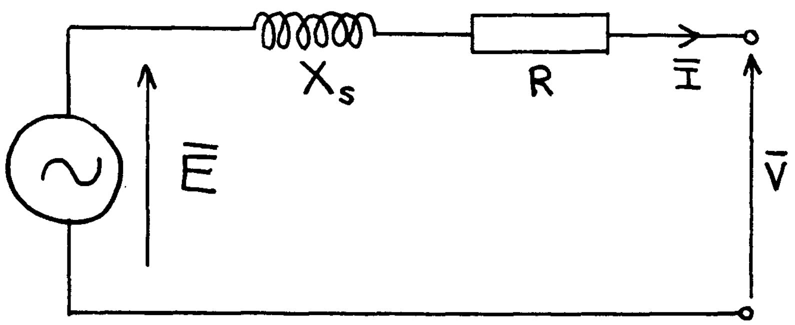


Figure 2

4 Open-circuit Test

The per-phase equivalent-circuit for the synchronous machine is shown in Fig. 3.



$$\bar{E} = \bar{V} + \bar{I}\,(R + jXs)$$

Figure 3

E is the emf induced in the ac stator winding by the rotor field current, i_f. The purpose of the open-circuit test is to determine the variation of E against i_f. This will allow us to predict the required field current for a given value of E in each of the load tests that you will undertake. At low values of i_f, E is proportional to i_f, but at high values saturation of the iron circuit occurs. Ask the demonstrator if you need further clarification of these points.

The induced emf, E, is measured simply by reading the terminal voltmeter on the stator winding. If the stator winding is open-circuit, $\bar{I} = 0$ and hence

$$\bar{E} = \bar{V}$$

The test procedure is as follows:

i) Ensure that the field control variac is set to zero and that the contactor on the stator windings of the synchronous machine is open.
ii) Start the dc motor (see Section 2) and adjust the speed to 1500 rpm.
iii) Increase the field current until the voltmeter on the stator winding reads a line voltage of 120 volts.
iv) Re-adjust the speed if necessary.

v) Record the field current and the open-circuit voltage (E).

i_f = ... Amps

E = ... Volts

vi) Assuming the machine to be linear, calculate the open-circuit ratio E/i_f

E/i_f = ... Ohms

vii) Increase the field current until the voltmeter reads the rated line voltage of 220 volts. Adjust the speed if necessary. Record the field current and the open-circuit voltage.

i_f = ... Amps

E = ... Volts

viii) Calculate the new open-circuit ratio E/i_f and explain why this is different from the ratio calculated at 120 Volts.

....

....

ix) Reduce the field current and speed to zero.

5 Short-Circuit Test

The function of the short-circuit test is simply to determine the value of X_S, the stator synchronous reactance, in the equivalent-circuit (see Fig 3). Assuming R << X_S, under short-circuit conditions V = 0 and

$$\overline{E} = j\,\overline{I}_{SC}X_S \qquad \text{or} \qquad X_S = \overline{E}/\overline{I}_{SC} \qquad (1)$$

Clearly we need to determine the variation of the short-circuit current, I_{SC}, against the induced emf, E, to calculate X_S. However it is clear from the open-circuit test that the induced emf, E, is controlled by the rotor field current, i_f. The short-circuit test therefore examines the variation of the short-circuit current against the rotor field current, i_f. The short-circuit test therefore examines the variation of the short-circuit current against the rotor field current, i_f. This information will allow you to determine the correct value of X_S for use in the load tests.

i) **Ensure that the field current is set to zero.**
ii) Short-circuit the stator terminals on the panel (see Fig 4).
iii) Increase the speed to 1500 rpm.

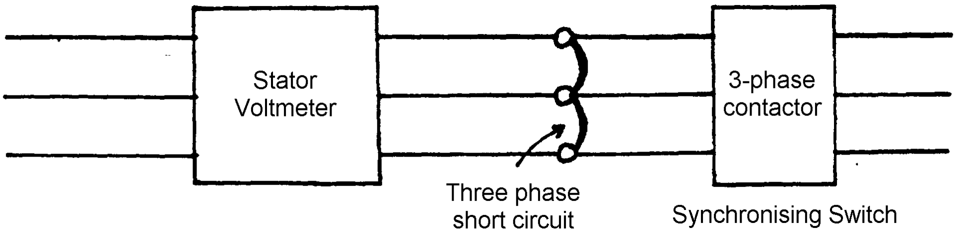


Figure 4

iv) Increase the field current SLOWLY from zero and take about four readings of the field current and the LINE current (I_{SC}) up to a line current of approximately 10 Amps. You should also ensure that the speed is 1500 rpm before you take each reading.

i_f (Amps)	I_{SC} (Amps) (LINE)	I_{SC} (Amps) (PHASE)

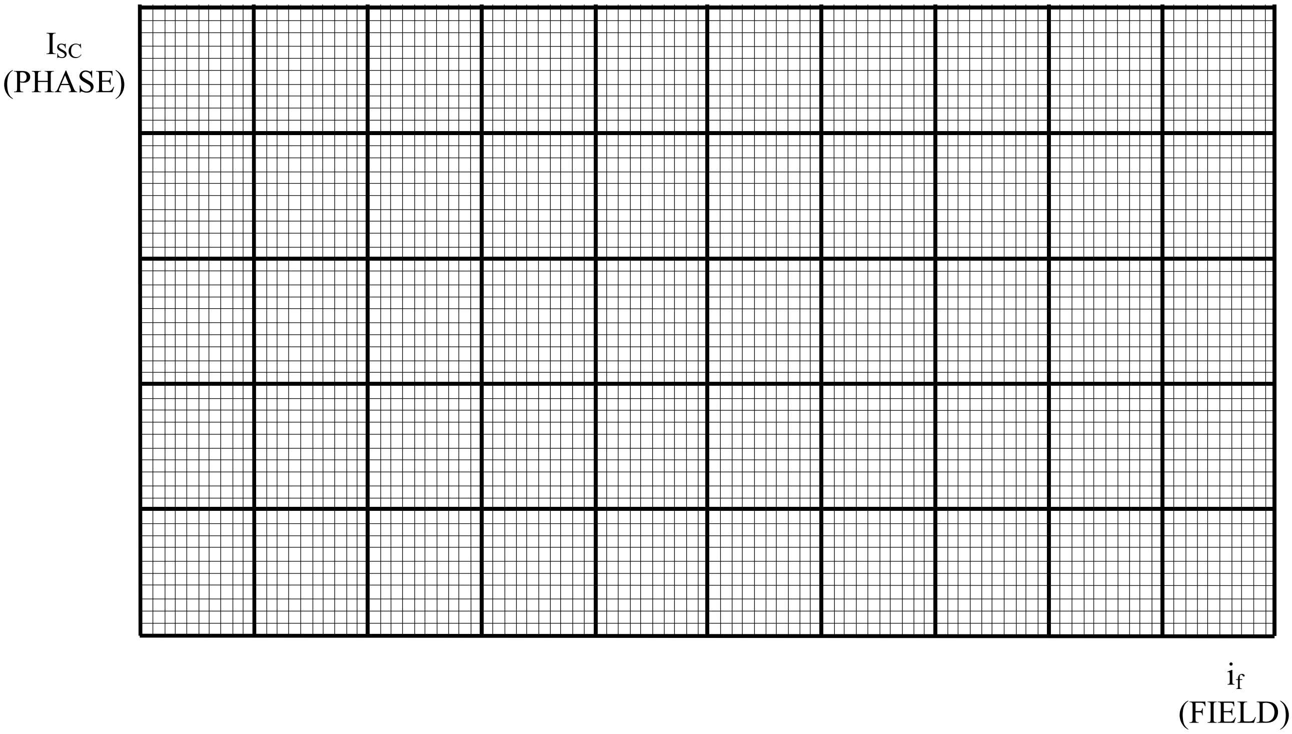
v) Keeping field current i_f fixed at your final value on the table, reduce the speed to 750 rpm. Record the short-circuit line current (I_{SC}). We shall return to this in the next section.

I_{SC} = ... Amps

vi) **Reduce the field current to zero and stop the machine. Remove the short-circuit from the stator.**

vii) Plot the phase current I_{SC} as a function of i_f. Determine the short-circuit ratio I_{SC}/i_f. This will be used in the next section to calculate X_S.

I_{SC}/i_f = ...



Determination of Equivalent-Circuit Parameters

The open-circuit and short-circuit tests examined the variation of E and I_{SC} against the rotor field current i_f. If we rewrite equation (1) for the synchronous reactance as follows

$$X_S = E/I_{SC} = (E/i_f) / (I_{SC}/i_f)$$

then you can determine a value for X_S from the ratios calculated in the open-circuit and short-circuit tests. In the open-circuit test, you should have noted that saturation reduced the open-circuit ratio E/i_f as you increased the field current. The simple equivalent circuit shown in Fig 3, however, does not easily account for saturation and as a consequence you will conduct your load tests at a reduced stator voltage (120 Volts) to avoid saturation effects. In determining the correct value of X_S, therefore, you should use the open-circuit ratio E/i_f appropriate to a stator voltage of 120 Volts.

X_S = ... Ohms

If your value of X_S is less than 30 Ohms, check you have used *phase* values rather than *line* values.

Rewriting equation (1) slightly differently, we see

$$I_{SC} = E/X_S$$

Consider this relation. Why did the short-circuit current recorded in section 5(v) remain essentially constant when the speed was reduced to 750 rpm?

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6 Synchronisation to the Laboratory Supply

In this section the objective is to connect the synchronous machine correctly to the three-phase laboratory supply. This is achieved by ensuring that the three-phase voltages on either side of the contactor (initially open) are:

a) of the same magnitude
b) at the same frequency
c) at the same phase angle.

If these conditions are satisfied, then the contactor may be closed and the machine will be connected to the supply without large currents flowing. The machine will then be 'locked' to the supply and any attempt to change its speed (ie using the dc motor) will result in power flowing to or from the supply.

The synchronisation conditions outlined above are monitored using the three simple light bulbs on your panel beside the synchronisation switch. These bulbs are connected as shown in Fig 5.

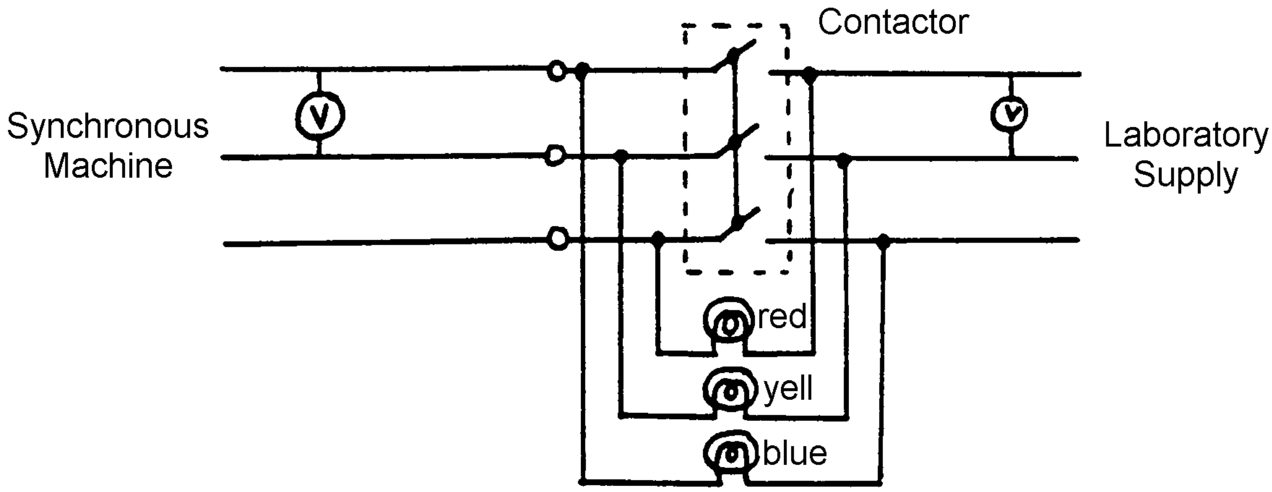

Figure 5

You can see that the top and bottom bulbs are cross-connected to different lines on either side of the switch whilst the centre bulb is connected to the same line. If conditions for synchronisation are correct, then you will find that the **top and bottom bulbs will be bright and the centre bulb will be dark**. Normally, the frequency, which will be controlled by the motor speed, will be slightly out and you will normally find that all the bulbs are **slowly** pulsing on and off.

The procedure for synchronisation is therefore as follows:

i) Ensure that the motor field current is ZERO and the contactor is OPEN. Ensure also that the Variac controlling the laboratory supply is set to zero.
ii) Adjust the speed of the motor to 1500 rpm.
iii) Increase the field current until the voltmeter reads a voltage of 120 Volts.
iv) Switch on the three-phase Variac for the laboratory supply and adjust until the voltmeter on the RH side of the switch also reads 120 Volts.
v) You should now find that the bulbs are pulsing on and off. Adjust the motor speed so that the bulbs are pulsing **very slowly**.
vi) Re-adjust that motor field current to give a voltage of 120 Volts if necessary.
vii) WAIT until the top and bottom bulbs are **equally bright** and the centre bulb is **out**. Close the contactor.

If you have done this correctly, there will be little or no current flowing and the bulbs will stop pulsing, indicating that the motor speed is now fixed by the supply frequency. If this is not the case, open the contactor immediately and ask one of the demonstrators for assistance.

7 On-Load Tests

With the machine synchronised, carry out load tests at each of the following operating points. For each point you should take readings of power, current, voltage and the field current.

1 Increase the field current (over-excited) to approximately 1.0 Amp. **Slowly** increase the speed control potentiometer until the **power** is approximately 700 Watts. Record readings in the table below as quickly as possible.

2 Reduce the field current (under-excited) to approximately 0.5 Amp. Adjust the speed control potentiometer until the **power** is approximately 450 Watts. Again record the following readings.

Line Voltage (V)	Field Current (A)	Line Current (A)	Power (W)

Increase the field to 0.7 Amp. **Reduce** the speed control potentiometer until the wattmeter indicates approximately zero power flow. **Reduce** the speed control potentiometer (anti-clockwise) by **one** further rotation. What happens to the wattmeter reading and the line current?

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Can you explain why this occurs?

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Open the contactor. Does this confirm your explanation above?

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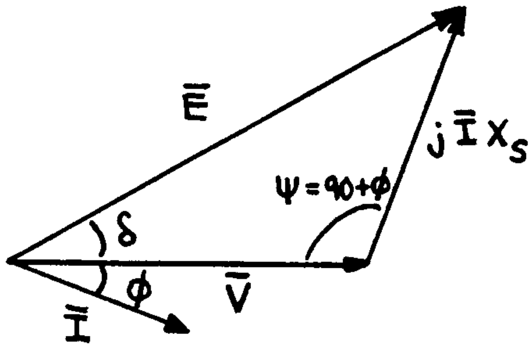
Reduce the field current to zero and then the speed to zero. **Switch off the laboratory voltage supply.**

8 Equivalent Circuit and Phasor Diagram

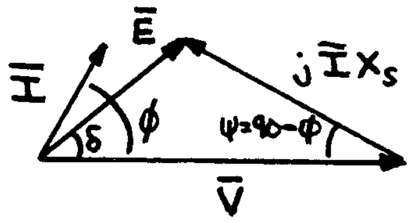
One of the objectives of this experiment is to demonstrate the accuracy of the equivalent-circuit for a synchronous machine by comparison with the on-load test measurements you have just recorded. Fig 3 illustrates the per-phase equivalent-circuit together with the terminal voltage equation. For each of your load tests you should use the appropriate phasor diagram shown in Fig 6, overleaf, to determine the field current. This can be compared directly with the value used in the load test.

i) Calculate the power factor from the measurements of power, voltage and current.

$$P = 3\ V_{PH} I_{PH} \cos\phi$$



Over-excited
$\Psi = 90 + \phi$



Under-excited
$\Psi = 90 - \phi$

Figure 6

NOTE: If your power factor is slightly greater than unity, set cosϕ = 1. Experimental errors usually account for this situation.

ii) Determine the angle on the appropriate phasor diagram, Ψ.
iii) Calculate the excitation voltage, E, using the cosine rule and your value of X_S.
iv) Determine the field current using your ratio E/i_f at 120 Volts.
Note: remember to use I_{PH} in these calculations as the model is *per phase*.

Load	Power Factor cosϕ (lead or lag)	ψ	Excitation Voltage E	Predicted i_f (A)	Measured i_f (A)
Over-excited Generator					
Under-excited Generator					

Why is it useful to be able to over-excite or under-excite the machine?

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Original Script – Dr R.A. McMahon
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