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ELEC ENG 3021 Electrical Energy Systems

Formal Practical Report for Synchronous Machines

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Declaration

The author, Zhiyang Ong [redacted], declare the following to be of his own work, unless otherwise referenced, as defined by The University of Adelaide's policy on plagiarism.

Abstract

The characteristics and constants of the synchronous machine were obtained. The open circuit, short circuit, synchronous impedance, and zero power-factor characteristics were determined. The constants that were calculated using various tests for the synchronous machine are the stator resistance, unsaturated direct-axis and quadrature synchronous reactances, and armature and leakage reactances. These helped the author to improve his understanding of the theory on three-phase synchronous machines.

Acknowledgements

The authors would like to thank Dr. WL Soong and the laboratory demonstrators for their help during the practical. The author also wishes to express his gratitude to Patrick Thompson Dale for his assistance as a partner for this practical.

Table of Contents

Abstract......ii
1.Experimental Aims......1
2.Nameplate Information......2
3.Measurement of Stator Resistance......3
4.Open-Circuit Test......4
    4.1.Experimental Results......4
    4.2.Discussion......6
5.Short-Circuit Test......8
    5.1.Experimental Results......8
    5.2.Discussion......9
6.Synchronous Impedance......11
    6.1.Experimental Results......11
    6.2.Discussion......13
7.Synchronisation......15
8.Load Test......15
    8.1 Experimental Results......15
    8.2 Discussion......18
9.Slip Test......20
    9.1 Experimental Results......20
    9.2 Discussion......21
10.Conclusion......22
11.References......23

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1. Experimental Aims

The aims of the experiment on “Synchronous Machines” are [1]:

i. Obtain the constants of a synchronous machine, such as its stator resistance, unsaturated direct-axis synchronous reactance X_d, unsaturated quadrature-axis synchronous reactance X_q, armature reactance, and leakage reactance.
ii. Determine the characteristics of the synchronous machine using the Open-Circuit, Short-Circuit, Zero Power-Factor, and Slip Tests. The characteristics to be obtained are open-circuit, short-circuit, synchronous impedance, and zero power factor characteristics.
iii. Acquire knowledge of data logging techniques associated with synchronous machines

These objectives will enable the students to gain practical experience of the theory of three-phase synchronous machines that was taught in lectures.

2. Nameplate Information

The nameplate data for the three-phase synchronous machine was recorded. The information found on the nameplate is tabulated in Table 2-1.

Table 2-1 Nameplate data of the synchronous machine

Rated information	Values
Frequency, f	50 Hz
Voltage, V_R	415 V
Speed, n_R	1500 rpm
Current, I_R	10.5 A
Horse Power	8 kW
Number	340

The number of poles, P, in the machine is determined as follows [2]:

$$P = 2 * 60 * f / n_s = 2 * 60 * 50 \text{ Hz} / 1500 \text{ rpm} = 4$$

Hence, there are four poles in the three-phase synchronous machine.

The base apparent power S is determined as follows [2]:

$$\begin{aligned} S &= \sqrt{3} * V_L * I_L \\ &= \sqrt{3} * 415 \text{ V} * 10.5 \text{ A} \\ &= 7.547 \text{ kVA} \end{aligned}$$

Therefore, the base apparent power is 7.547 kVA.

The base resistance R_R is determined as [2]:

$$\begin{aligned} R_R &= V_R / I_R \\ &= 415 \text{ V} / 10.5 \text{ A} \\ &= 39.52\ \Omega \end{aligned}$$

The base resistance R_R is 39.52 **Ω**.

3. Measurement of Stator Resistance

The stator resistance of the three-phase synchronous machine between each pair of phases are measured and tabulated in Table 3-1.

Table 3-1 Stator resistance of the synchronous machines between each pair of phases

Pair of phases	Resistance (Ω)
R_{AB}	2.1
R_{AC}	2.1
R_{BC}	2.2
Average, R_{avg}	2.1

The average resistance R_{avg} between a pair of phases is calculated as [1]:

$$\begin{aligned} R_{avg} &= ⅓ * (R_{AB} + R_{AC} + R_{BC}) \\ &= ⅓ * (2.1 + 2.1 + 2.2)\ \Omega \\ &= 2.1\ \Omega \end{aligned}$$

The stator resistance R_1 can be calculated as follows [1][3]:

$$\begin{aligned} R_1 &= ½ * R_{avg} * (1 + \text{skin effect}) \\ &= ½ * R_{avg} * (1 + 0.05) \\ &= ½ * 2.1\ \Omega * 1.05 \\ &= 1.12\ \Omega \\ &\approx 1.1\ \Omega \end{aligned}$$

Hence, the stator resistance R_1 is 1.1 Ω and is the average resistance per phase. It is determined as half of the average resistance between a pair of phases. It is multiplied by 105% to take into account the skin effect of the current passing through the stator windings. See [3] for more information about skin effect.

Therefore, the per unit value of the stator resistance is: $R_1 / R_R = 1.1\ \Omega / 39.52\ \Omega = 0.02783$

4. Open-Circuit Test

4.1. Experimental Results

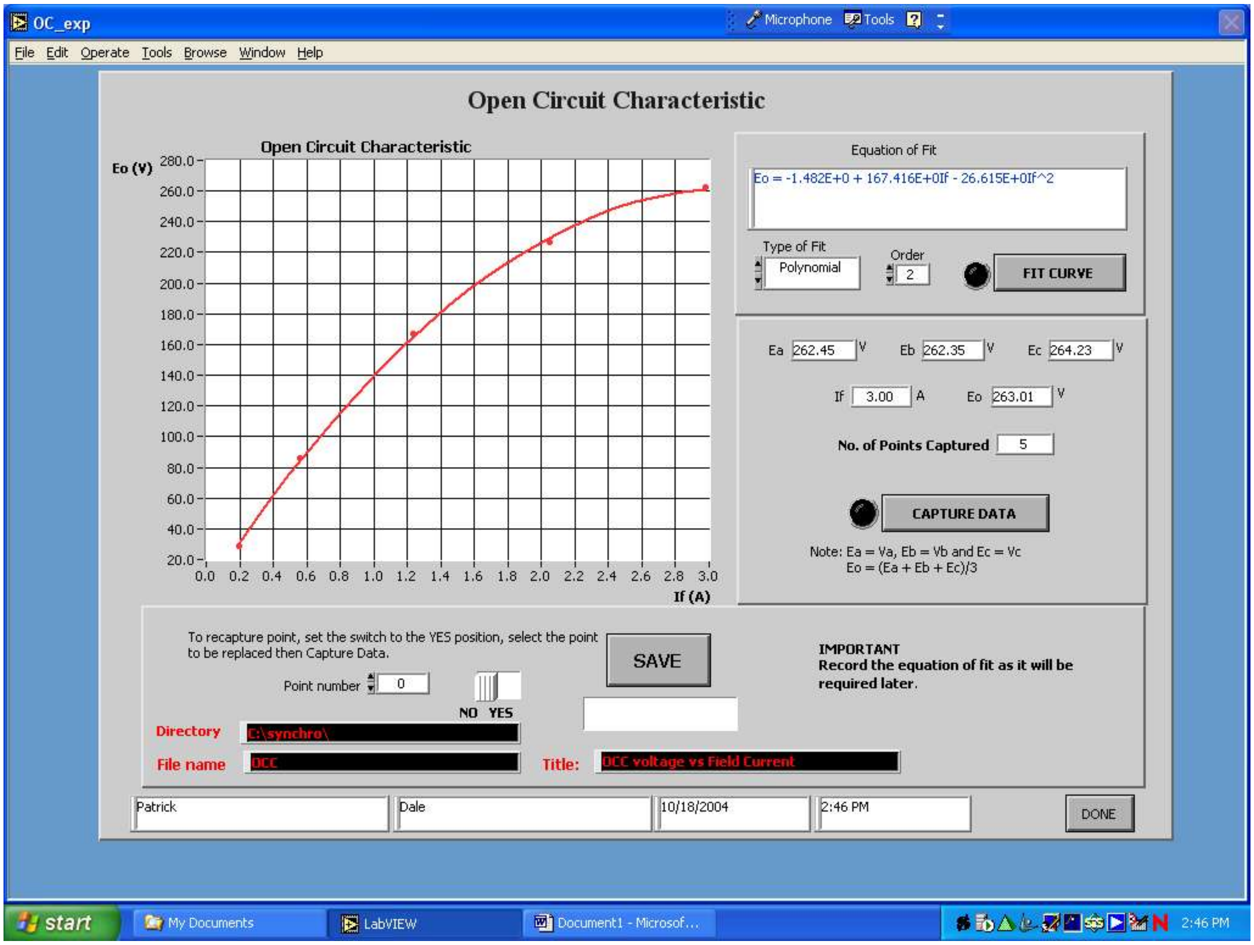
The experiment was conducted according to the experimental procedure listed in Section 4.3.1 of the laboratory handout [1]. The results of the open-circuit test are indicated as follows:

Table 4-1 indicates the values of open-circuit induced voltage source across the airgap for corresponding field currents. These values are obtained during the experiment by varying the "Excitation Field" rheostat to reduce the resistance for increasing values of field current. They are used by the open-circuit characteristic measurement program to plot the graph of open-circuit characteristic.

Table 4-1 Values of open-circuit voltage for corresponding field current

Open-circuit voltage E_o (V)	Field Current (A)
28.8909	0.1978
85.6758	0.5618
166.7024	1.2318
226.7064	2.0513
262.1235	2.9758

Figure 4-1 shows the front panel of the open-circuit characteristic measurement program. The left side of the panel indicates a graph of the open-circuit characteristic obtained in the open-circuit test. It is not a straight line; see Section 4.2 for discussion on its shape.



Eo = -1.482E+0 + 167.416E+0If - 26.615E+0If^2

Type of Fit: Polynomial
Order: 2

Ea 262.45 V Eb 262.35 V Ec 264.23 V

If 3.00 A Eo 263.01 V

No. of Points Captured 5

Note: Ea = Va, Eb = Vb and Ec = Vc
Eo = (Ea + Eb + Ec)/3

To recapture point, set the switch to the YES position, select the point to be replaced then Capture Data.

Point number 0

IMPORTANT
Record the equation of fit as it will be required later.

Directory C:\synchro\

File name OCC

Title: OCC voltage vs Field Current

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Figure 4-1 Front panel of the open-circuit characteristic measurement program

It can be observed that 110% of the rated line voltage was not exceeded by the induced output voltage. The values for the ordinate E_o are for the induced voltage source across the airgap. They are displayed as phase voltages. Hence, the corresponding line voltage of E_o for its maximum value of 262.1 V is:

$E_o = \sqrt{3} * 262.1 \text{ V} = 454.0 \text{ V}$

The value for 110% of the rated line voltage is: 110% * 415 V = 456.5 V

Thus, 110% of the rated line voltage was not exceeded by the induced voltage across the airgap.

The author was unable to obtain more points for fitting a curvilinear line on the data set since field current cannot be decreased in the open-circuit test due to magnetic hysteresis effects. The author had problems attempting to get a good range of data values as the field current increases at an increasing rate for each small incremental change in the resistance of the excitation field [1].

4.2.Discussion

The section contains the discussion for questions posed in the laboratory handout pertinent to the open circuit test.

The shape of the open-circuit characteristic is curvilinear since magnetic hysteresis effects are brought about by the increase in the field current of the synchronous machine. As the field current is increased by reducing the resistance of the excitation field, the reluctance of the iron path decreases as a function of field current due to magnetic saturation [1]. This corresponds to decreases in armature reactance X_A. Hence, the stator flux increases given the same magnetomotive force [2]. Consequently, the total magnetic field in the synchronous machine increases and induces the airgap voltage E. As the rate of stator flux increases at a decreasing rate, the induced voltage increases at a decreasing rate with respect to increasing field current.

By extrapolating the airgap line, which is the straight line approximation of the open-circuit characteristic for low values of field current, the measured open-circuit voltage is observed to be negative when the field current is zero [1]. This non-zero open-circuit voltage is due to the small voltage ($I * R_1$) drop in the stator. As the output current I passes through the stator windings, there exists a small voltage drop in the stator [4]. This value is estimated by the negative y-intercept of the equation for the curvilinear line used to fit the set of data points in Figure 4-1. From Figure 4-1, the equation of fit is:

$$E_o = -26.615 * (I_f)^2 + 167.416 * I_f - 1.482 \qquad (1)$$

Hence, the voltage drop in the stator, y-intercept of (1), is –1.482 V.

A straight line, indicated in black on Figure 4-2, is fitted on the open-circuit characteristic for low values of field current. Using the graph divisions, the slope m_{oc} of this line is:

$$m_{oc} = \Delta E_o / \Delta I_f = (180\text{ V} - 60\text{ V}) / (1.2\text{ A} - 0.4\text{ A}) = 150\text{ V/A} = 150\ \Omega$$

The slope of the open-circuit characteristic indicates the impedance of the stator.

The field current at which the curve deviates significantly from the straight line is approximately 0.8 A. This can be observed from Figure 4-2.

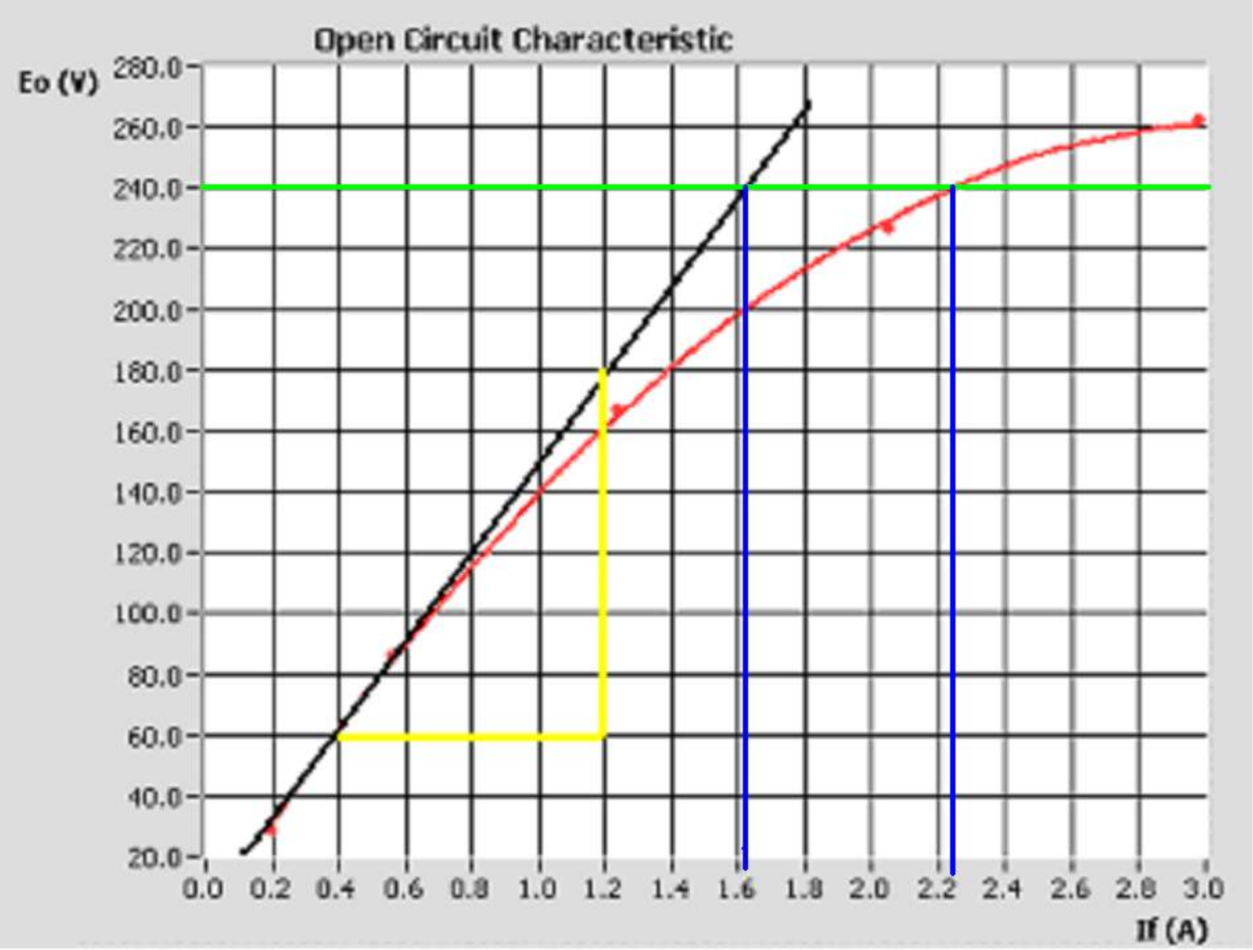


Figure 4-2 **Fit of a straight line on the open-circuit characteristic at low-field currents**

A horizontal line, in green, corresponding to the rated phase voltage is drawn in the graph of Figure 4-2. The field currents required to produce the rated voltage using the open-circuit characteristic and the airgap line are 2.4 A and 1.6 A approximately.

5. Short-Circuit Test

5.1. Experimental Results

The short circuit test was conducted according to the experimental procedure listed in Section 4.4.1 of the laboratory handout [1]. The results and discussion are indicated as follows.

Table 5-1 indicates the values of short-circuit stator current I_{SC} for corresponding values of field current I_f whilst Figure 5-1 indicates the screenshot of the front panel for the short-circuit test. These values in Table 5-1 are obtained during the experiment by varying the "Excitation Field" rheostat to reduce the resistance for increasing values of field current. They are used by the short circuit characteristic measurement program to plot the graph of short circuit characteristic.

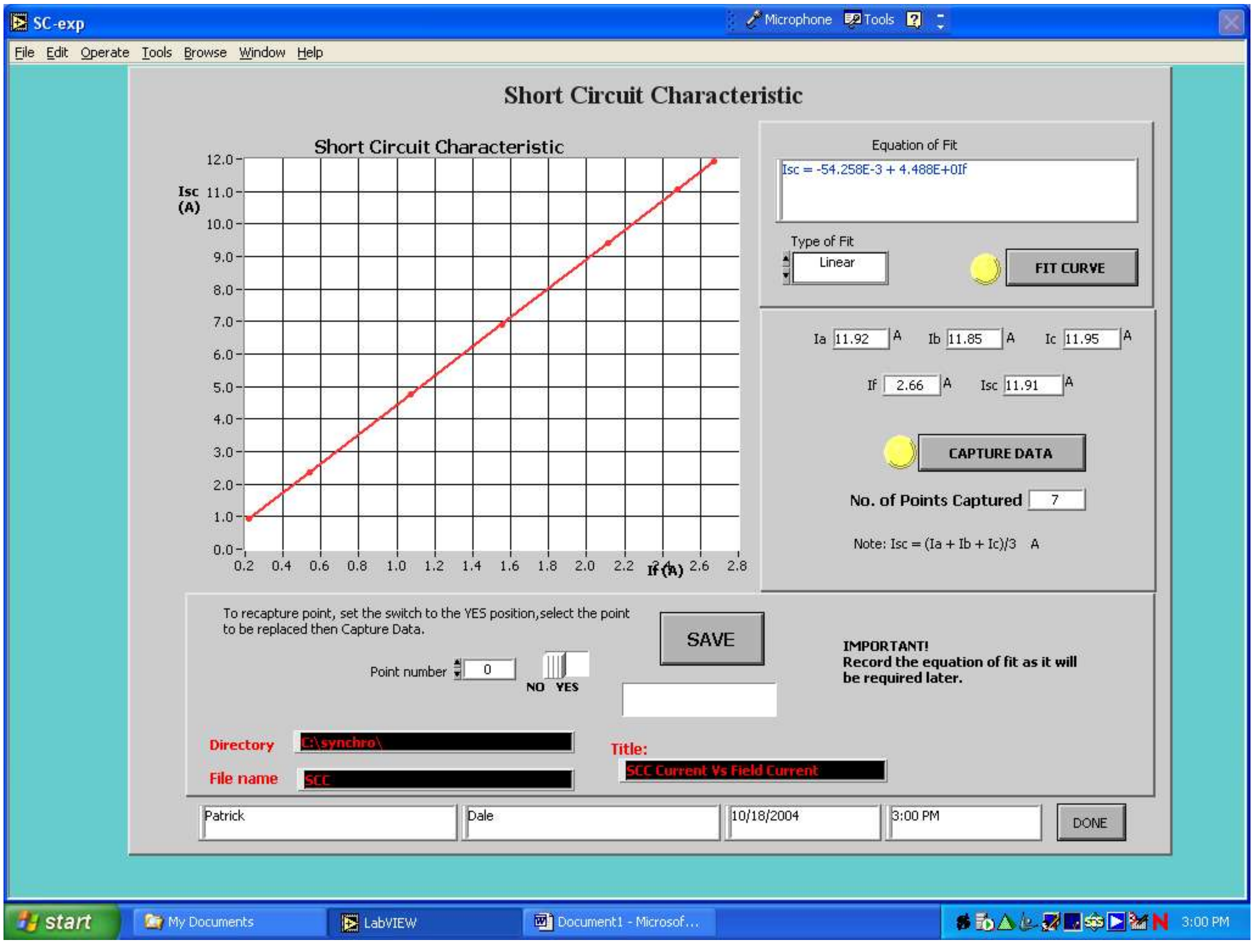
In Figure 5-1, the left side of the panel indicates a graph of the short circuit characteristic obtained in the short circuit test. It is a straight line; see Section 5.2 for discussion on its shape. The values for the ordinate I_{SC} are for the short circuit stator current whilst the abscissa I_f is the field current. The maximum value of the short circuit stator current is 11.6 A.
The value for 110% of the rated current is: $110\% * I_R = 110\% * 10.5 \text{ A} \approx 11.6 \text{ V}$
Thus, it can be observed that the 110% value of the rated current was exceeded by 2.6 % since percentage overshoot M_o for short circuit current is:

$$M_o = (\text{maximum } I_{SC} - 110\% * I_R) / (110\% * I_R) = (11.9 - 11.6) / 11.6 \approx 2.6\%$$

However, this percentage overshoot of 2.6% is not significant.

Table 5-1 Values for short-circuit stator current I_{SC} for corresponding values of field current I_f

Short circuit stator current, I_{SC} (A)	Field Current, I_f (A)
0.9429	0.2188
2.3577	0.5381
4.7458	1.0723
6.9147	1.5543
9.4172	2.1109
11.0645	2.4768
11.9378	2.6696



Equation of Fit: Isc = -54.258E-3 + 4.488E+0If

Type of Fit: Linear

Ia 11.92 A Ib 11.85 A Ic 11.95 A

If 2.66 A Isc 11.91 A

No. of Points Captured 7

Note: Isc = (Ia + Ib + Ic)/3 A

To recapture point, set the switch to the YES position, select the point to be replaced then Capture Data.

Point number 0

IMPORTANT!
Record the equation of fit as it will be required later.

Directory C:\synchro\

File name SCC

Title: SCC Current Vs Field Current

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Figure 5-1 **Front panel of the short-circuit test program**

5.2.Discussion

The section contains the discussion for questions posed in the laboratory handout pertinent to the short circuit test.

The shape of the short-circuit characteristic is linear since the magnetic circuit does not saturate under short circuit conditions and the air gap flux remains at a low level. The magnetic circuit remains unsaturated for large field and armature currents since the resultant magnetomotive force from the stator and rotor magnetic fields is small [1][2]. Thus, for an unsaturated synchronous machine, the induced voltage E across the airgap will increase linearly with field current I_f. Consequently, the stator current will increase linearly with the field current [5].

The equation for the linear line used to fit the set of data points in Figure 5-1 is:

$$I_{SC} = 4.488 * I_f - 54.258 * 10^{-3} \qquad (2)$$

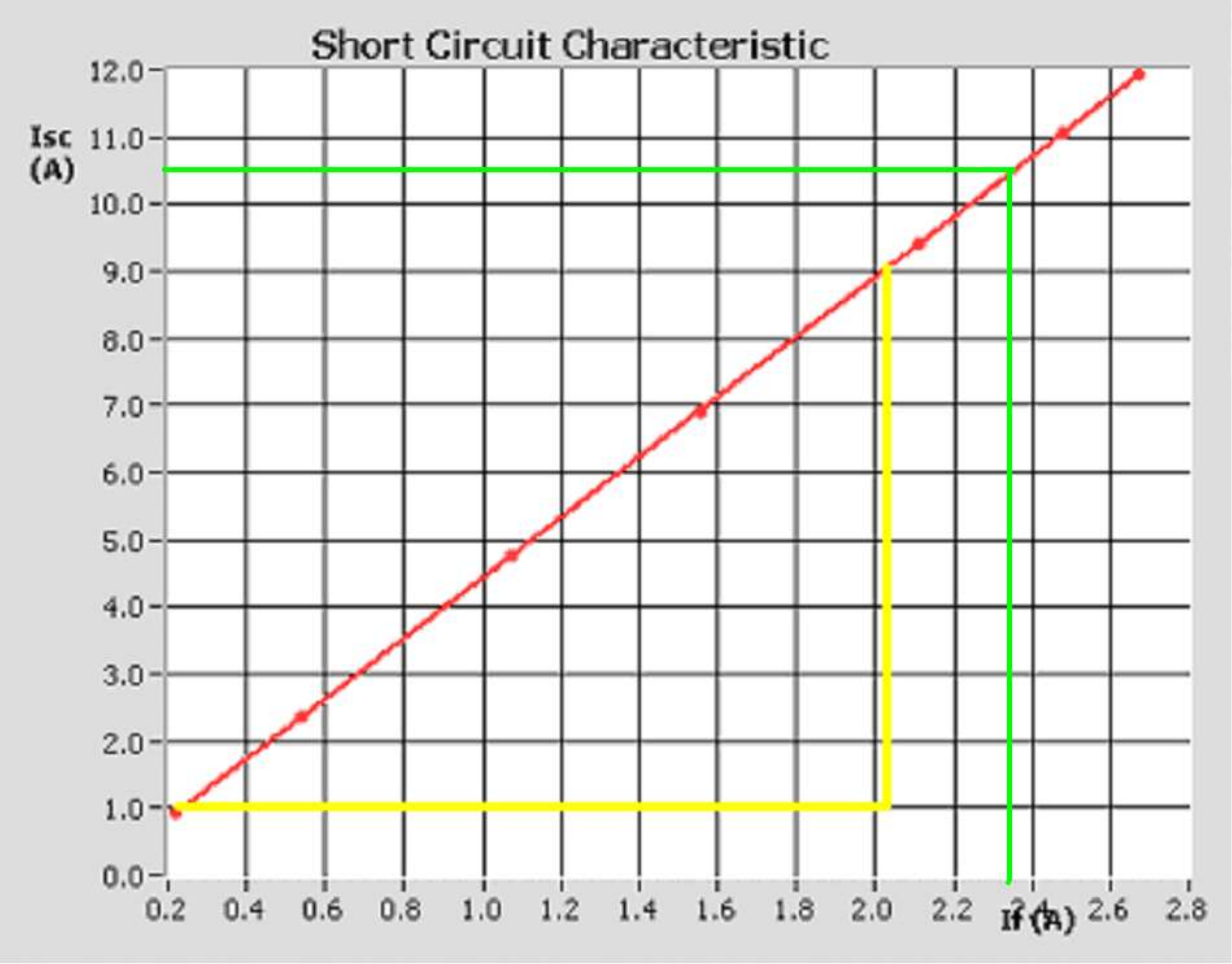


Figure 5-2 **Short circuit characteristic with construction lines to determine its gradient**

Using graph divisions and construction lines drawn in yellow on the graph of the short circuit characteristic, as shown in Figure 5-2, the slope m_{sc} of this linear short circuit characteristic is:

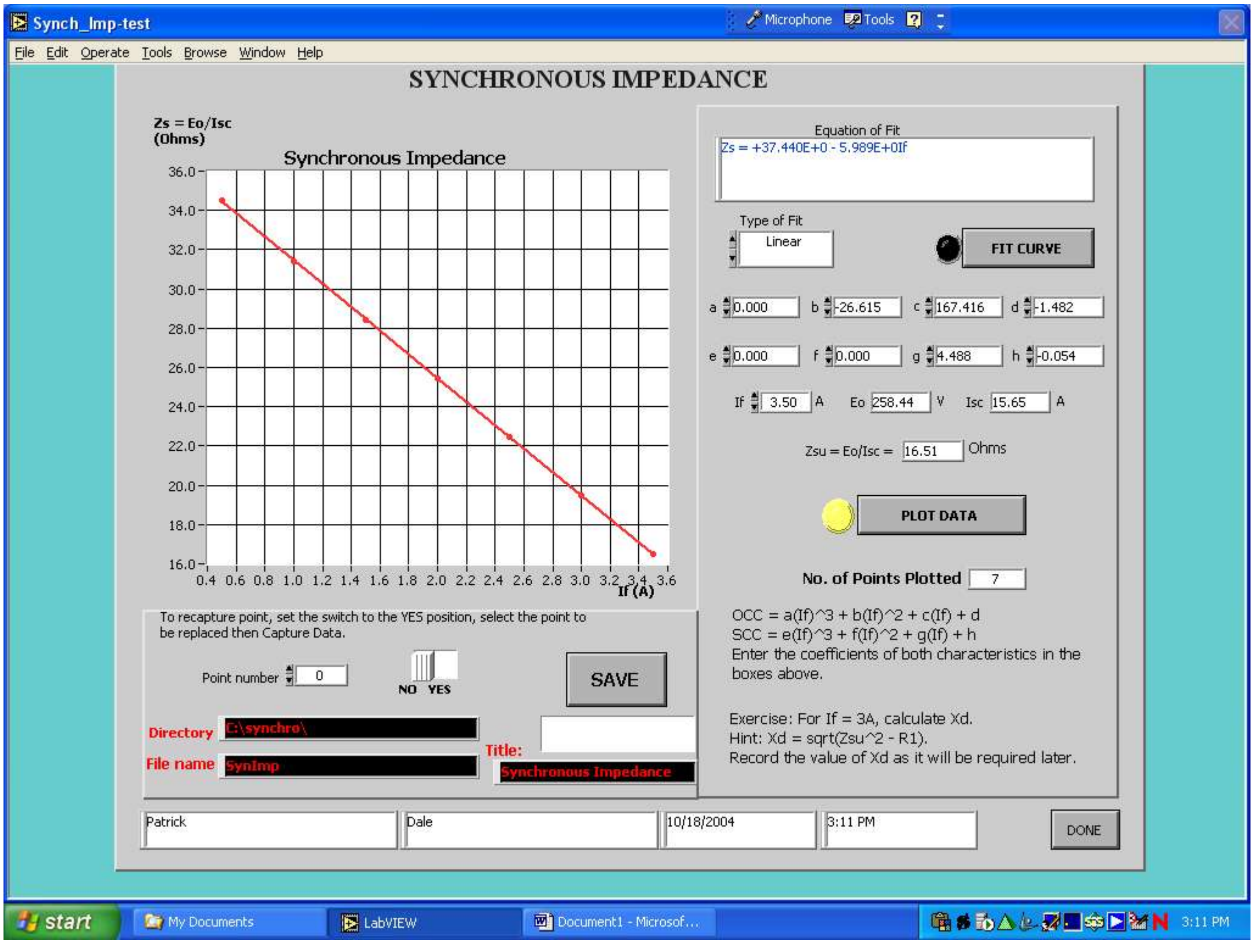
$$m_{sc} = \Delta I_{SC} / \Delta I_f = (9.0\ V - 1.0\ V) / (2.02\ A - 0.22\ A) = 4.4\ A/A$$

The field current required to produce the rated stator current of 10.5 A is 2.34 A. This is obtained by drawing construction lines for the rated stator current to determine its corresponding field current on the short-circuit characteristic. These lines are indicated in Figure 5-2 as green lines.

6. Synchronous Impedance

6.1. Experimental Results

This part of the synchronous machine experiment was conducted according to the experimental procedure listed in Section 4.5.1 of the laboratory handout [1]. The results and discussion are indicated as follows.



Equation of Fit: Zs = +37.440E+0 - 5.989E+0If

Type of Fit: Linear

a 0.000 b -26.615 c 167.416 d -1.482

e 0.000 f 0.000 g 4.488 h -0.054

If 3.50 A Eo 258.44 V Isc 15.65 A

Zsu = Eo/Isc = 16.51 Ohms

No. of Points Plotted 7

OCC = a(If)^3 + b(If)^2 + c(If) + d
SCC = e(If)^3 + f(If)^2 + g(If) + h
Enter the coefficients of both characteristics in the boxes above.

Exercise: For If = 3A, calculate Xd.
Hint: Xd = sqrt(Zsu^2 - R1).
Record the value of Xd as it will be required later.

To recapture point, set the switch to the YES position, select the point to be replaced then Capture Data.

Point number 0

Directory C:\synchro\

File name SynImp

Title: Synchronous Impedance

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Figure 6-1 **Front panel of synchronous impedance calculation program**

Figure 6-1 shows the screenshot of the front panel for the calculation of the synchronous impedance program. The magnitude of the synchronous impedance, which is defined as the ratio of open-circuit voltage E induced across the airgap over the short circuit stator current corresponding to the same field current I_f [1]. Thus, the graph indicated on the left panel of Figure 6-1 is that of synchronous impedance Z_S as a function of field current I_f.

It is observed that the synchronous reactance function is not a downward sloping curvilinear graph as it should be. This could be due to the inadequate amount of data points for the open circuit characteristic test; see Section 4.2 for further details. It should resemble the graph shown in Figure 6-2.

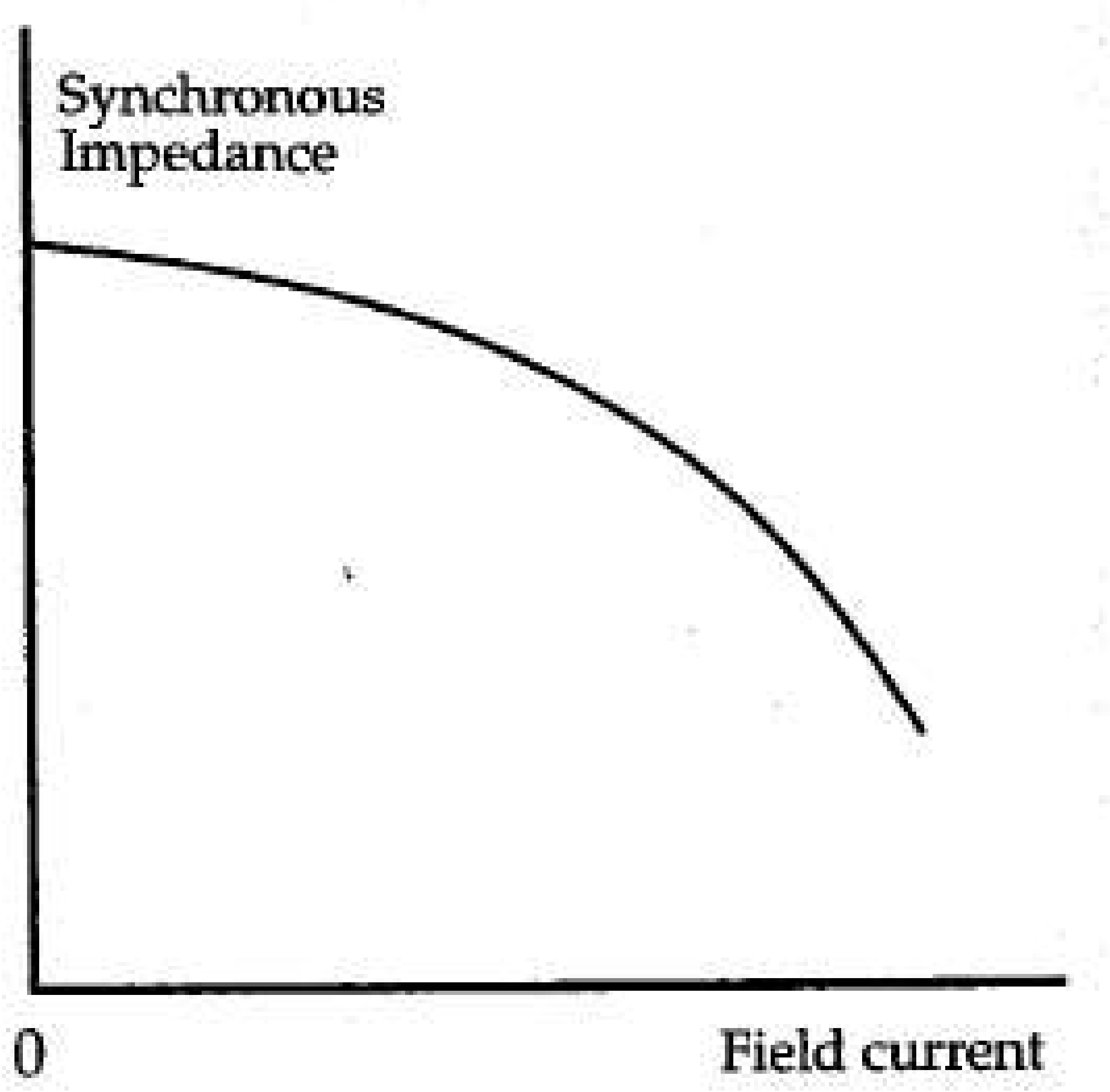


Figure 6-2 Synchronous impedance characteristic as a function of field current [1]

The coefficients of the equations (1) and (2), for the open and short circuit characteristics respectively, are entered into the right panel of the synchronous impedance program indicated in

Figure 6-1. Subsequently, increasing values of field currents were entered for the program to determine the corresponding synchronous impedance for each field current [1]. The synchronous impedance curve, also shown in Figure 6-1, was then plotted by the program. Since the synchronous machine is not saturated under short circuit conditions and magnetic saturation can be ignored for small values of field current, the synchronous impedance is constant. Consequently, it is also called unsaturated synchronous impedance Z_{su}.

For the determined constant value of unsaturated synchronous impedance Z_{su}, indicated in Figure 6-1, the value of saturated synchronous reactance X_d is determined at the field current of 3 A as:

$$\begin{aligned} X_d &= \sqrt{((Z_{su})^2 - R_1)} \\ &= \sqrt{((16.51\ \Omega)^2 - 1.12\ \Omega)} \\ &=16.476\ \Omega \\ &\approx 16.48\ \Omega \end{aligned}$$

The line of best fit for the unsaturated synchronous reactance line is:

$$Zs = -5.989 * I_f + 37.440 \qquad (3)$$

6.2.Discussion

The expected unsaturated value of synchronous impedance Z_{su} is calculated by the ratio of the gradient of the open circuit characteristic m_{oc} over that of the short circuit characteristic m_{sc}.

$$Z_{su} = m_{oc} / m_{sc} = (150\ \Omega) / (4.4\ A/A) \approx 34.09\ \Omega$$

The base resistance R_R, 39.52 Ω, is the same as the base impedance Z_B.
Hence, the per unit value of the expected unsaturated value of synchronous impedance Z_{su} is:

$$X_{su} \text{ (per unit)} = X_{su} / Z_B = 34.09\ \Omega / 39.52\ \Omega = 0.8626 \text{ p.u.}$$

For the determined constant value of unsaturated synchronous impedance X_{su}, the value of unsaturated d-axis synchronous reactance X_{du} is determined as:

$$\begin{aligned} X_{du} &= \sqrt{((Z_{su})^2 - (R_1)^2)} \\ &= \sqrt{((34.09\ \Omega)^2 - (1.12\ \Omega)^2)} \\ &=34.07\ \Omega \\ &\approx 34.07\ \Omega \end{aligned}$$

Hence, the per-unit value of X_{du} is:

X_{du} (per unit value) = $X_{du} / Z_B = 34.07\ \Omega / 39.52\ \Omega = 0.8622$ p.u.

Hence, the per-unit value of X_d is:

X_d (per unit value) = $X_d / Z_B = 16.476\ \Omega / 39.52\ \Omega = 0.4169$ p.u.

The ratio of the saturated value of X_d calculated at 3 A to the unsaturated d-axis synchronous reactance X_{du} is:

$X_d / X_{du} = 16.476\ \Omega / 34.07\ \Omega = 0.4836$

7. Synchronisation

The synchronisation of two synchronous machines was conducted according to the experimental procedure listed in Section 4.6.1 of the laboratory handout [1]. This is carried out to prepare for the Zero Power Factor Test, which is subsequently described in Section 7. When the two synchronous machines are synchronised, their voltage sources have the same voltage, frequency, phase angle, and phase sequence.

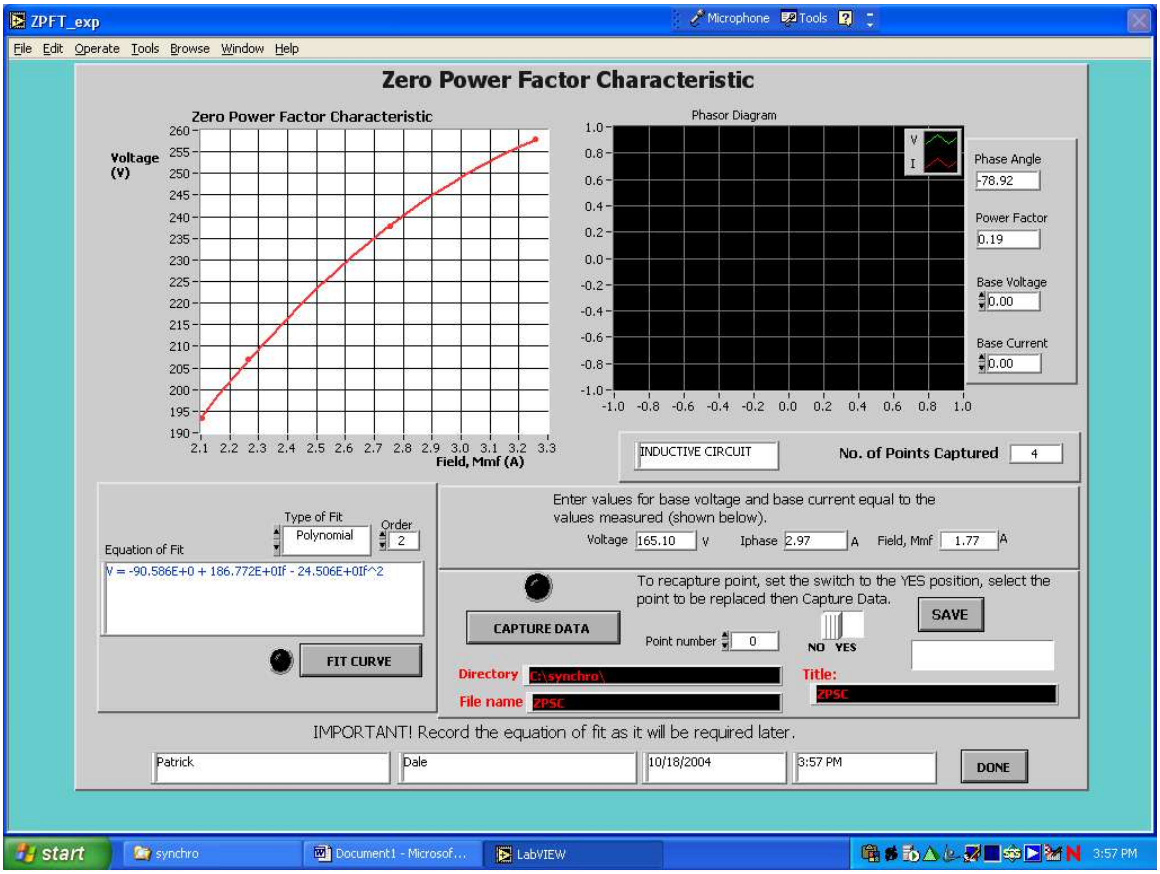
To match the frequencies and magnitude of the voltages of the two synchronous machines, the speed of the synchronous machine can be adjusted to change the frequencies and the field current can be changed to adjust the voltage magnitudes. The speed can be adjusted with the “RHEO”, which is the field winding variable resistance of the DC machine, and the field current can be adjusted with the “Excitation Field” rheostat.

8. Load Test

8.1 Experimental Results

The Zero Power-Factor Test was conducted according to the experimental procedure listed in Section 4.7.1 of the laboratory handout [1]. The results and discussion of the procedure are indicated as follows.

Different data values of terminal voltage V_t are obtained for increasing values of field current I_f, and the Zero Power-Factor Characteristic is plotted as a function of V_t against I_f. The Zero Power-Factor Characteristic is shown on the left side of Figure 8-1. Since the values of excitation cannot be decreased to lower the values of field current and prevent hysteresis effects from affecting the integrity of the data, the author was only able to obtain 4 data values as the field current increased rapidly for small increments in the resistance of the excitation field at large values of field current.



Phase Angle: -78.92

Power Factor: 0.19

Base Voltage: 0.00

Base Current: 0.00

INDUCTIVE CIRCUIT

No. of Points Captured: 4

Type of Fit: Polynomial

Order: 2

Equation of Fit: V = -90.586E+0 + 186.772E+0If - 24.506E+0If^2

Enter values for base voltage and base current equal to the values measured (shown below).

Voltage 165.10 V Iphase 2.97 A Field, Mmf 1.77 A

To recapture point, set the switch to the YES position, select the point to be replaced then Capture Data.

Point number: 0

Directory: C:\synchro\

File name: ZPSC

Title: ZPSC

IMPORTANT! Record the equation of fit as it will be required later.

Patrick

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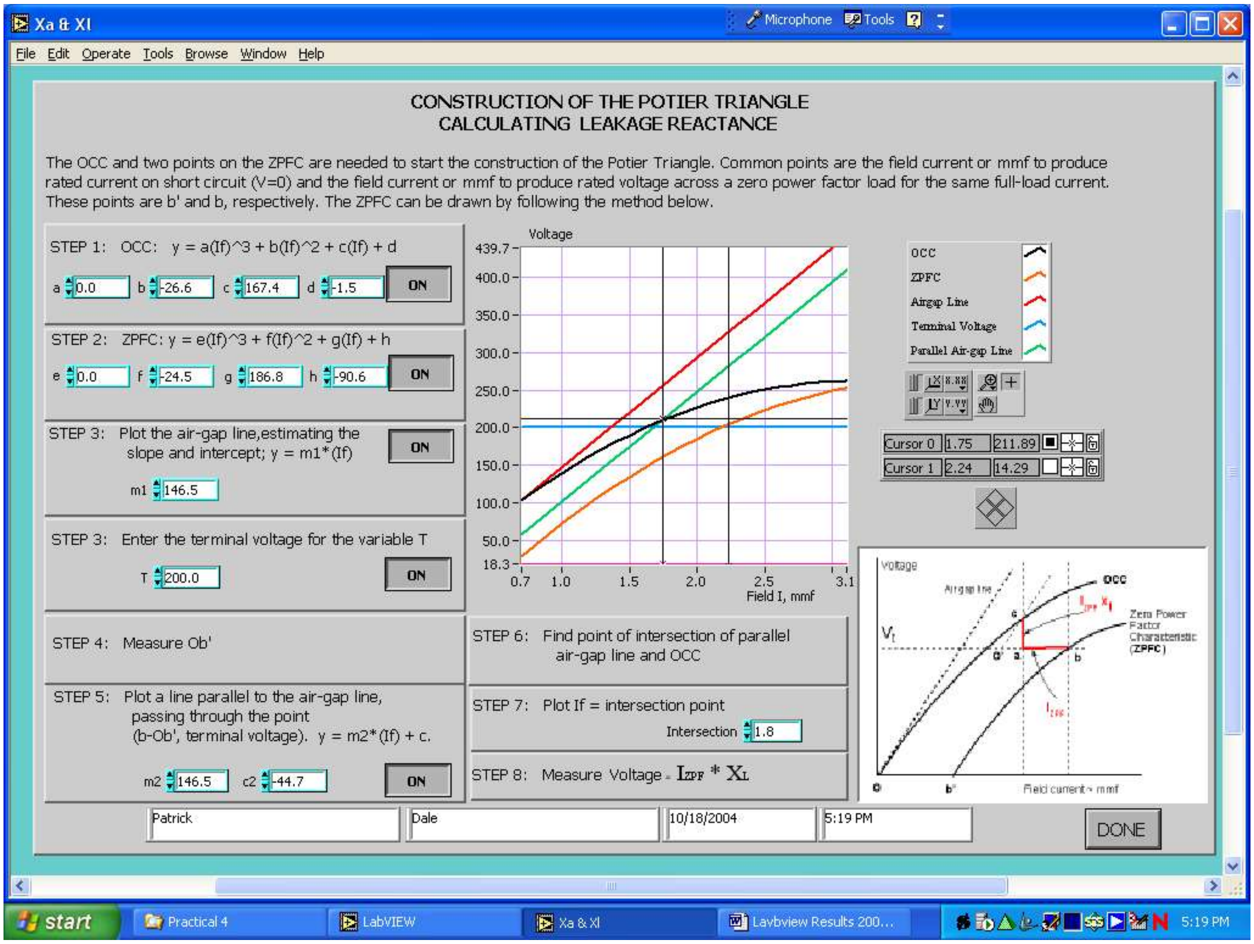
Figure 8-1 Front panel of the Zero Power-Factor Test program

The equation of the line, Zero Power-Factor Characteristic, which best fits these data points is:

$$V = -24.506 * (I_f)^2 + 186.772 * I_f - 90.586 \qquad (4)$$

It can be observed that the Zero Power-Factor Characteristic is fairly linear. This could be due to the insufficient data points used in plotting the Zero Power-Factor Characteristic. The author expects the Zero Power-Factor Characteristic to be significantly more curved if there exists seven or more data points.

Next, the Potier triangle calculation program is loaded to determine the armature and leakage reactances. Once again, the coefficients of equations (1) and (4), open circuit characteristic and zero power-factor test characteristic, are entered so that their corresponding graphs can be determined. These graphs are indicated in Figure 8-2.



CONSTRUCTION OF THE POTIER TRIANGLE
CALCULATING LEAKAGE REACTANCE

The OCC and two points on the ZPFC are needed to start the construction of the Potier Triangle. Common points are the field current or mmf to produce rated current on short circuit (V=0) and the field current or mmf to produce rated voltage across a zero power factor load for the same full-load current. These points are b' and b, respectively. The ZPFC can be drawn by following the method below.

STEP 1: OCC: y = a(If)^3 + b(If)^2 + c(If) + d
a 0.0 b -26.6 c 167.4 d -1.5

STEP 2: ZPFC: y = e(If)^3 + f(If)^2 + g(If) + h
e 0.0 f -24.5 g 186.8 h -90.6

STEP 3: Plot the air-gap line,estimating the slope and intercept; y = m1*(If)
m1 146.5

STEP 3: Enter the terminal voltage for the variable T
T 200.0

STEP 4: Measure Ob'

STEP 5: Plot a line parallel to the air-gap line, passing through the point (b-Ob', terminal voltage). y = m2*(If) + c.
m2 146.5 c2 -44.7

STEP 6: Find point of intersection of parallel air-gap line and OCC

STEP 7: Plot If = intersection point
Intersection 1.8

STEP 8: Measure Voltage = $I_{ZPF} * X_L$

Cursor 0 1.75 211.89
Cursor 1 2.24 14.29

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Figure 8-2 **Front panel of the Potier triangle calculation program**

The gradient m_1 of the open circuit characteristic for small values of I_f is determined as the ratio of the vertical displacement over the horizontal displacement of the points $(x_1,y_1) = (0.0, 0.0)$ and $(x_2, y_2) = (0.82, 120.15)$.

$$m_1 = (y_2 - y_1) / (x_2 - x_1)$$
$$= (120.15 - 0.0) / (0.82 - 0.0)$$
$$= 146.5$$

Since the open circuit characteristic passes through the point of origin, neglecting the voltage drop in the stator, the y-intercept of the tangent to the open circuit characteristic for small values of field current is zero. Hence, the airgap line passes through the origin.

A terminal voltage of 200 V is entered and the distance Ob' is measured as 0.52 A. Hence, the location of O' is given as the difference between the point b and the distance Ob' on the line of a 200 V terminal voltage. Point b is the intersection between the zero power-factor characteristic and the terminal voltage of 200 V. The corresponding field current $I_{f(b\text{-}Ob')}$ at the location of O' is the difference between the corresponding field current of b and the corresponding field current of Ob':

$I_{f(b\text{-}Ob')}$ = 2.19 A – 0.52 A = 1.67 A

A line parallel to the airgap line is to be drawn; this line has a gradient m_2 that is equal to that of the airgap line, m_1. Hence, the y-intercept c of this line is:

$y = m_2 * I_{f(b\text{-}Ob')} – c$
$c = y - m_2 * I_{f(b\text{-}Ob')}$
$= (200 – 146.5 * 1.67)$ V
$= –44.653$ V

Consequently, the values of c and m_2 are entered into the Potier triangle calculation program. The point of intersection between the parallel airgap line and the open circuit characteristic is (1.75 A, 211.89 V). The stator current I_{ZPF} at which the zero power-factor test was conducted at is 3.07 A.

8.2 Discussion

The voltage difference ($I_{ZPF} * X_L$) between the point of intersection and the 200 V terminal voltage is:

Voltage difference = $I_{ZPF} * X_L$ = 211.89 V – 200.00 V = 11.89 V

Hence, the leakage reactance X_L can be determined as:

X_L = voltage difference / I_{ZPF}
= 11.89 V / 3.07 A
= 3.873 **Ω**

Thus, the per unit value of the leakage reactance X_L is:

X_L (per unit) = X_L / Z_B
= 3.873 **Ω** / 39.52 **Ω**
= 0.09800 p.u.

The d-axis armature reactance X_{da} is calculated as:

$X_{da} = X_d – X_L$
= 16.476 **Ω** – 3.873 **Ω**
= 12.60 **Ω**

Hence, the per unit value of X_{da} is:

X_{da} (per unit) $= X_{da} / Z_B$
$= 12.60\ \Omega / 39.52\ \Omega$
$= 0.3188$ p.u.

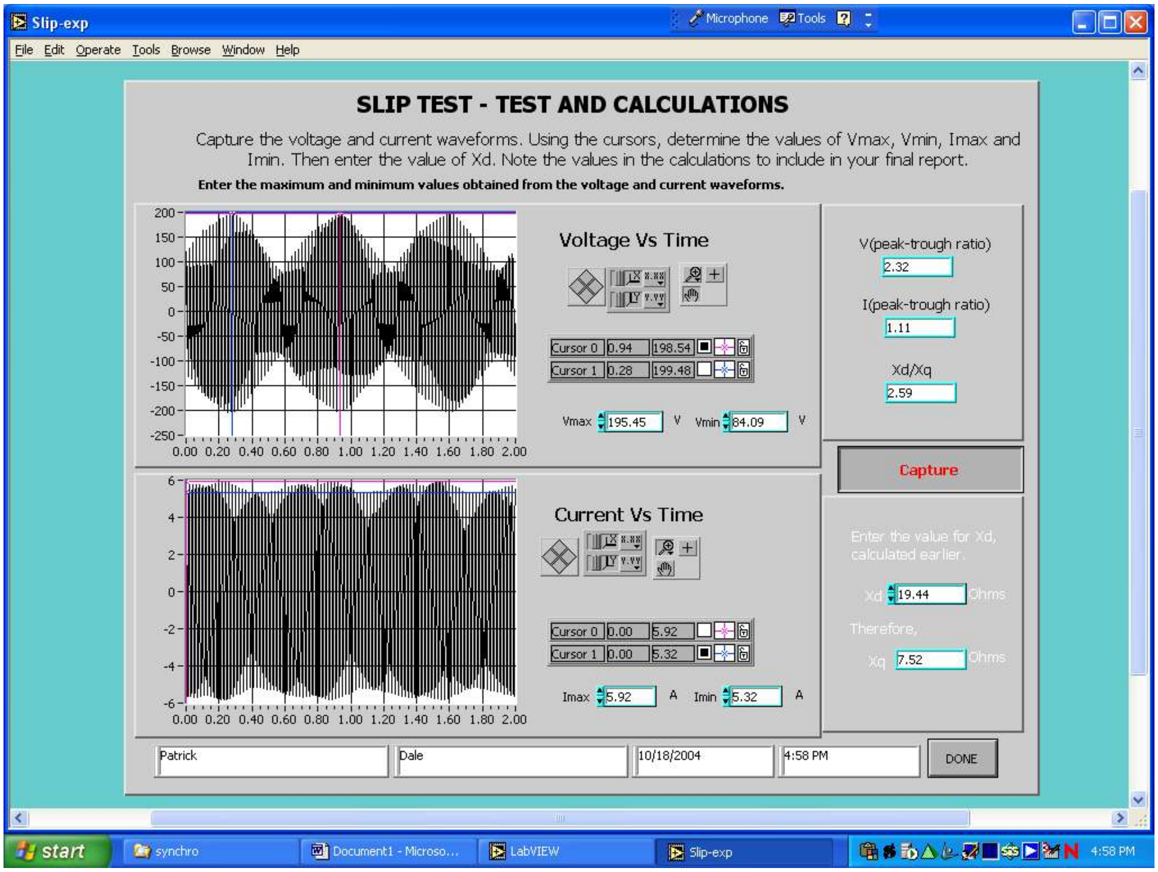
Hence, the fractions of d-axis armature reactance X_{da} and leakage reactance X_L over the d-axis reactance X_d at the field current of 3 A are:

$X_{da} / X_d = 12.60\ \Omega / 16.476\ \Omega = 0.7647\ \Omega/\Omega$
$X_L / X_d = 3.873\ \Omega / 16.476\ \Omega = 0.2351\ \Omega/\Omega$

9. Slip Test

9.1 Experimental Results

The Slip Test was conducted according to the experimental procedure listed in Section 4.8.1 of the laboratory handout [1]. The results and discussion of the procedure, to measure the ratio of direct and quadrature reactances in the salient pole synchronous machine, are indicated as follows.



SLIP TEST - TEST AND CALCULATIONS

Capture the voltage and current waveforms. Using the cursors, determine the values of Vmax, Vmin, Imax and Imin. Then enter the value of Xd. Note the values in the calculations to include in your final report.

Enter the maximum and minimum values obtained from the voltage and current waveforms.

Voltage Vs Time:

Cursor 0 0.94 198.54

Cursor 1 0.28 199.48

Vmax 195.45 V Vmin 84.09 V

Current Vs Time:

Cursor 0 0.00 5.92

Cursor 1 0.00 5.32

Imax 5.92 A Imin 5.32 A

V(peak-trough ratio) 2.32

I(peak-trough ratio) 1.11

Xd/Xq 2.59

Enter the value for Xd, calculated earlier.

Xd 19.44 Ohms

Therefore,

Xq 7.52 Ohms

Patrick

Dale

10/18/2004

4:58 PM

Figure 9-1 Front panel of the slip test measurement program

The cursor provided with the graphs of current versus time and voltage versus time are used to determine the maximum and minimum values of current and voltages. The maximum and minimum values of voltage are 195.45 V and 84.09 V; the maximum and minimum values of current are 5.92 V and 5.32 V.

The ratio of direct reactance over the quadrature reactance is 2.59. However, the value of direct reactance entered into the program to determine the quadrature reactance is wrong due to a previous miscalculation. Thus, the correct value of quadrature reactance is:

$$X_d / X_q = 2.59$$
$$X_q = X_d / 2.59$$
$$= 16.48\ \Omega / 2.59$$
$$= 6.363\ \Omega$$

Hence, the per unit value of X_q is:

$$X_q \text{ (per unit)} = X_q / Z_B = 6.363\ \Omega / 39.52\ \Omega = 0.1610\ \Omega$$

The cursors are also used to estimate the period of the amplitude modulation of the voltage waveform. The period T is determined as:

$$T = t_2 - t_1 = 0.94 \text{ s} - 0.28 \text{ s} = 0.66 \text{ s}$$

Hence, the frequency f of the amplitude modulation is:

$$f = 1 / T = 1/0.66 \text{ s} = 1.515 \text{ Hz}$$

Since the frequency of the amplitude modulation corresponds to the slip frequency, the slip frequency s_f is 1.515 Hz.

9.2 Discussion

The slip frequency s_f is the product of the slip s and frequency f of the voltages and currents in the stator. From Section 9.1, s_f is 1.515 Hz whilst f is 50.0 Hz.
Hence, $s = s_f / f = 1.515 \text{ Hz} / 50.0 \text{ Hz} = 0.03030$
Therefore, the machine speed n during the speed test is determined as follows:

$$s = (n_s - n) / n_s$$
$$n = n_s - s * n_s = 1500 \text{ rpm} - 0.03030 * 1500 \text{ rpm} = 1455 \text{ rpm}$$

Hence, the machine speed during the slip test is 1455 rpm.

Using Equation (9) of the laboratory handout, the approximation of the ratio of direct-axis synchronous reactance X_d and quadrature reactance X_q is given as [1]:

$$X_d / X_q = (195.45 \text{ V} / 84.09 \text{ V}) * (5.92 \text{ A} / 5.32 \text{ A}) = 2.586 \approx 2.59$$

Hence, the calculation performed by the program for the ratio X_d / X_q is correct.

10. Conclusion

The list of calculated synchronous machine parameters in both ohms and per-unit for a field current of 3 A is indicated in Table 10-1. These parameters are the stator resistance, direct-axis reactance, quadrature-axis reactance, and the leakage reactance.

Table 10-1 Summary of synchronous machine parameters in ohms and per-unit values

Synchronous machine parameter	Ohm (Ω)	Per unit (p.u.)
stator resistance	1.1	0.02783
direct-axis reactance	16.476	0.4169
quadrature-axis reactance	6.363	0.1610
leakage reactance	3.873	0.09800

The characteristics and constants of the synchronous machine were obtained. The open circuit, short circuit, synchronous impedance, and zero power-factor characteristics were determined. Lastly, the constants that were calculated using various tests for the synchronous machine are the stator resistance, unsaturated direct-axis and quadrature synchronous reactances, and armature and leakage reactances.

11. References

[1] N Ertugrul and WL Soong, *Laboratory Handout for Module 4: Synchronous Machines*, The University of Adelaide, Adelaide, 2004

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