EACH STUDENT ATTENDING THIS LAB SHOULD READ CAREFULLY THE
SAFETY PRECAUTIONS BELOW, SIGN THIS COVER SHEET AND RETURN IT TO
YOUR LAB TUTOR

- STUDENTS ARE WARNED OF POSSIBLE ELECTRIC SHOCK RISK AND
  FIRE RISK IN THE LAB AREA.
- STUDENTS ARE REQUIRED TO WEAR STOUT SHOES OR BOOTS WITH
  ENCLOSED TOES. BARE FEET, THONGS, OPEN TOE SANDALS AND HIGH
  HEELS ARE NOT ACCEPTABLE. TUTORS AND LAB STAFF MAY REFUSE
  ADMITTANCE TO THE LAB TO STUDENTS WITH INADEQUATE
  FOOTWEAR
- NO FOOD OR DRINK IS ALLOWED IN THE LAB.
- THIS EXPERIMENT INVOLVES THE ASSEMBLY AND RUNNING OF AN
  ELECTRIC MOTOR. WHEN ENERGISED AND ROTATING THE MOTOR
  REPRESENTS A HAZARD IF FINGERS OR OTHER OBJECTS ARE INSERTED
  INTO THE MACHINE. THE EXPERIMENTAL PROCEDURE DOES NOT
  REQUIRE STUDENTS TO COME IN CONTACT WITH THE MOVING PARTS
  OF THE MOTOR
- LONG HAIR AND LOOSE CLOTHING MAY BECOME CAUGHT IN THE
  MACHINE AND CAUSE INJURY. LONG HAIR MUST BE APPROPRIATELY
  Restrained. NO LOOSE CLOTHING TO BE WORN. JEWELLERY SHOULD
  NOT BE WORN. TUTORS AND LAB STAFF MAY REFUSE ADMITTANCE TO
  THE LAB TO STUDENTS WITH INAPPROPRIATE CLOTHING OR
  UNRESTRAINED LONG HAIR
- AS THE BENCH POWER SUPPLIES HAVE 150 V AC AVAILABLE, THE TESTS
  COVERED IN THIS LAB CAN BE LETHAL IF A MISTAKE IS MADE.
- FIND OUT THE LOCATION OF YOUR NEAREST EMERGENCY STOP
  BUTTON BEFORE STARTING.
- DO NOT TURN ON THE SUPPLY UNTIL YOU HAVE DRAWN THE CIRCUIT
  DIAGRAM AND YOUR CONNECTIONS HAVE BEEN CHECKED BY YOUR
  TUTOR.
- DO NOT DISCONNECT ANY LEADS WHILE THE SUPPLY IS ON.
- ALWAYS SET THE VARIABLE VOLTAGE TO ZERO BEFORE TURNING ON
  THE SUPPLY.
- RETURN THE VOLTAGE TO ZERO BEFORE SWITCHING OFF, UNLESS
  THERE IS AN EMERGENCY.
- REMEMBER TO DIAL 6 FOR EMERGENCY.
- REMEMBER TO DIAL 0000 FOR AMBULANCE.

I have read these precautions and shall carry them out.
Signed: (Please sign)
**Aims**

To observe the operation of a permanent magnet, brushless DC motor.
To be familiar with the integration of electronics and machines.
To review the output voltage waveform of a 6-switch inverter.
To review the motor back emf - speed and torque - current relationships.

**Methodology**

Most disc drives, computer fans, robots, and NC machine tools are driven by brushless permanent-magnet DC motors for long life, low noise, cool operation, and compact size. Most of these motors use Hall-effect switches to sense rotor position (which separates these motors from stepping and other synchronous motors), but sensorless control is also possible using motor back emf and other methods.

This laboratory will demonstrate a brushless DC motor (3-phase 4-pole stator; 4-pole ferrite permanent-magnet rotor), a DC to 3-phase mosfet inverter and a sensorless controller.

**Equipment**

*Provided by UTS in Room 1816*

Lybotec bench with power supplies, connecting leads with retractable shrouds on the plugs 3-phase, 4-pole stator (150V, 2A) and 4-pole, ferrite, permanent-magnet rotor, as shown in Figure 1.
DC to 3-phase MOSFET transistor inverter (200V, 10A DC), as pictured in Figure 2, with user supplied gate drive inputs. The inverter block diagram can be found in the same folder with this lab note on the UTSonline subject website.

Sensorless controller (SC), as shown in Figure 3, with internal settings of R = 7.9 “off” (27K + 6.2K) and C = 10 “on” (0.47uF).
Rectifier (150V, 10 A), tachometer, meter set
Shaft encoder and counter, digital multimeter, oscilloscope, printer and cables.

Provided by student:
Further writing paper, Graph paper

Reading
1. Lecture notes on Brushless DC motors
2. Hughes "Electric Motors & Drives: Fundamentals Types & Applications"
3. Kenjo "Brushless DC Motors"
4. Miller "Brushless Permanent-Magnet and Reluctance Motor Drives"
5. Chai "Electromechanical Motion Devices"
6. Rashid “Power Electronics: Circuits, Devices and Applications”, Chap. 8
Theory -1. Timing and voltage waveforms

A 6-switch inverter is to be used to control a 3-phase, star-connected, brushless DC motor with 6 steps in the output voltage waveform. There will always be 2 phases “on” at any moment. Sketch the circuit diagram of the power circuit, showing the motor and DC supply.

(i) Circuit diagram

(ii) Sketch the mosfet switch gate drive waveforms:

(iii) Sketch two of the inverter phase to negative rail voltage waveforms and hence sketch one phase-to-phase waveform applied to the motor:
**Theory - 2. Motor back emf and speed**

If PWM is not used in the inverter, the brushless DC motor DC supply $V_d$ is related quite closely to the AC line-neutral rms voltage $V_a$ by:

$$V_d = 2.22 \, V_a$$

The fundamental component of the motor phase (line-neutral, L-N) back emf, $E_a$, is proportional to the speed $\omega_r$ (rad/s) and the phase flux linkage, $\lambda_m$. The proportional coefficient $k_E$ (Vs/rad) relating $\omega_r$ to $E_a$ is known as the motor phase emf constant,

$$E_a = k_E \omega_r.$$ 

(iv) If the motor line to neutral emf $E_a$ is assumed to be sinusoidal and of value 40 V rms at 100 rad/s, calculate the emf constant:

$$k_E = \text{[Calculation]} = \text{[Value]} \text{Vs/rad}.$$

(v) Calculate the speed in rad/s and rev/min at a DC supply voltage of 40 V and no load.

At $V_d = 40$ V, motor rms L-N voltage $V_a = \text{[Value]}$.

At no load ($I_a=0$) motor rms L-N voltage $V_a = \text{rms L-N back emf} E_a$.

Hence, $E_a = \text{[Calculation]}$.

Thus the no-load speed $\omega_{r0} = \text{[Calculation]} \text{rad/s}$

$= \text{[Calculation]} \text{rev/min}.$

(vi) Sketch a graph of expected AC voltage and speed against DC voltage:

(vii) Each motor phase can be modelled electrically as the back-emf source $E_a$ connected in series with a resistance $R$ and an inductance $L$ (usually called the "synchronous inductance"). The phasor equation assuming sinusoidal excitation is then

$$\hat{V}_a = \hat{E}_a + R\hat{I}_a + j\omega L\hat{I}_a,$$

where the electrical angular frequency $\omega = p\omega_r$ for a motor with $p$ pole pairs. Assuming that the phase reactance is negligible and that the back emf and current are in phase, obtain an expression for $\omega_r$ as a function of the rms motor phase current $I_a$ and DC voltage $V_d$. 

5
(viii) Sketch the characteristic $\omega_r = f(I_a)$ for $R = 9.3 \ \Omega$ and $V_d = 40 \ \text{V}$, and estimate the rotor speed in RPM at a load corresponding to $I_a = 0.66 \ \text{A}$. Estimate the motor phase current $I_{a,lk}$ in the locked rotor case ($\omega_r = 0$).

**Theory - 3. Motor torque and current**

If PWM is not used in the inverter, and switching takes place at the optimum time, the mean DC supply current $I_d$ is related approximately to the AC line rms fundamental current $I_a$ by

$$I_d = 1.28 \ I_a$$

The motor electromagnetic torque $T_e$ (in Nm) is proportional to the rms phase current if aligned with the back-emf, the proportional coefficient $k_T$ (in Nm/A) being known as the motor torque constant per phase:

$$T_e = 3 \ k_T \ I_a$$

for a 3-phase motor with optimum switching. Note that the motor emf constant is the same as the motor torque constant per phase: $k_E = k_T = p \lambda_m$, where $p$ is the number of pole pairs.

(ix) If a load torque of $0.5 \ \text{Nm}$ is applied to the above motor, calculate the rms fundamental AC line current and the mean DC supply current.

AC current $I_a =$ \hspace{1cm} = \hspace{1cm} = \hspace{1cm} A

DC current $I_d =$ \hspace{1cm} = \hspace{1cm} = \hspace{1cm} A

(x) Sketch a graph of expected motor current against torque:
(xi) Again, assuming that the phase reactance is negligible and the phase current is aligned with the back-emf, obtain an expression for $\omega_r$ as a function of the motor torque $T_e$.

(xii) Sketch the motor mechanical characteristic $\omega_r = f(T_e)$ for $R = 9.3 \, \Omega$ and $V_d = 40 \, V$, and estimate the rotor speed at a load of 0.5 Nm and 1 Nm.

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**Method and results**

Work on the same colour bench as for Lab 5. Report any damage that may occur.

Use only digital and moving coil meters for the AC phase measurements, not moving iron meters as they need too much power to operate.

Assemble the 3 phase stator and the permanent magnet rotor.

(1) Use the DC bench power supply to feed about 1A through the three windings of the stator wired in series and determine the average DC resistance of a phase by measuring the voltage across all three phases. Calculate the average motor phase resistance $R$.

$I_a = \:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\: A$
Measured voltage = $\:\:\:\:\:\:\:\:\:\:\:\:\:\:\: V$
Average phase resistance = $\:\:\:\:\:\:\:\:\:\:\:\:\:\:\: \Omega$

(2) Connect the digital oscilloscope up across one phase of the stator and spin the rotor by hand to record a few cycles of the back emf. Use this waveform to calculate the motor voltage constant $k_E$.

Estimated phase to neutral fundamental voltage = $\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\: V_{pp} = \:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\: V_{rms}$
Back emf period = $\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\\: \:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\\:

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(3) Connect the bench DC supply to the inverter DC input via a DC ammeter and the inverter AC outputs to each phase of the motor 3-phase stator with an AC ammeter in one phase. Connect the other terminals of the 3-phase stator together to form a star connection. Connect the sensorless controller inputs to the inverter 3 phase motor outputs (make sure the phases Y-B-R are connected in the right order). Connect the sensorless controller output to the inverter gate drive input with a DB15 to DB15 cable.

Add a DC voltmeter to measure the DC supply voltage, and an AC voltmeter to measure the line-neutral motor voltage. Draw the circuit diagram:

(4) **No load test**

Carefully insert the 4-pole ferrite rotor. Fit the shaft encoder, connect up the counter and connect its speed output to a digital voltmeter. Increase the supply voltage until the motor starts (it should start at about 12V DC). Determine the conversion between voltmeter reading and speed. Record the speed, voltages and currents in the table below as the DC voltage is increased after the motor starts. Include a set of measurements for 40V DC supply.

<table>
<thead>
<tr>
<th>DC supply voltage, $V_d$ (Vdc)</th>
<th>DC supply current, $I_d$ (mA dc)</th>
<th>L-N phase voltage, $V_a$ (Vrms)</th>
<th>Phase current, $I_a$ (mA rms)</th>
<th>Speed $\omega$ (volts)</th>
<th>Angular speed $\omega$ (rad/s)</th>
<th>Calculated $k_E$ Vs/rad</th>
<th>Calculated $V_d/V_a$</th>
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(5) Allowing for the motor phase resistance but assuming negligible phase reactance, calculate from the table above the average motor voltage constant $k_E$. Compare this to the value obtained by spinning the shaft by hand. Calculate the average ratio $V_d/V_a$ in the table above and compare it to the ratio stated in the Theory section.
(6) Plot the DC current, AC voltage, AC current, speed (in RPM) against DC voltage.

(7) Based on the calculated values of $k_E$ and $R$, and neglecting the phase reactance, sketch the characteristics $\omega_r = f(I_a)$ for 40V DC supply voltage and one other DC supply voltage recorded in section (4).

(8) Use an oscilloscope to record the following motor voltage waveforms: (a) line to line, (b) line to neutral, (c) line to inverter negative rail, (d) neutral to inverter negative rail. Compare with your expected waveform in Theory section (iii). Comment on any differences.

(9) **Load test**
Assuming $k_E = k_T$, allowing for the motor phase resistance and neglecting the phase reactance, sketch the expected motor mechanical characteristic $\omega_r = f(T_e)$ (speed in RPM) for 40V DC supply voltage.
(10) Run the motor at 40V DC supply voltage. Apply a load to the motor shaft using the method described below. Note the increase in DC and AC current. Record the dc supply current, phase current, speed and spring balance force applied. Measure the torque arm used.

DC supply voltage $V_d =$ volts
Torque arm = m

<table>
<thead>
<tr>
<th>DC supply current, $I_d$ (mA dc)</th>
<th>Phase current, $I_a$ (mA rms)</th>
<th>Speed $\omega$ (volts)</th>
<th>Angular speed $\omega$ (rad/s)</th>
<th>Force $F$ (N)</th>
<th>Calculated torque $T_e$ (Nm)</th>
<th>Calculated $k_T$ (Nm/A)</th>
<th>Calculated $I_d/I_a$</th>
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**Method of applying load torque to the motor:**
A wheel is fitted to the motor shaft. A string is wrapped around the shaft wheel approximately one turn and the end of the string which will be in tension is tied to a metal ring which is placed over one of the motor frame posts. The other end of the string is gently pulled to control the torque applied to the shaft and adjusted to give the desired motor current.

When it is time to measure the torque, a spring balance is hooked around the metal ring and enough force is applied to lift the ring away from the post. The torque is controlled as before and spring balance is read at the desired motor current.

(11) From the table above, calculate the average motor torque constant $k_T$ and compare it to $k_E$. Calculate the average ratio $I_d/I_a$ in the table above and compare it to the ratio given in the Theory section.
(12) Plot phase current $I_a$, speed $\omega$ (in RPM) and DC supply current $I_d$ against torque $T_e$. Compare the plot with the expected mechanical characteristic $\omega_r = f(T_e)$ sketched in (9). Comment.

(13) What connection changes would be required to reverse the motor direction? Try it.

**Report**

1. Before arriving for the laboratory, complete the calculations and graphs in the theory section.
2. Complete the measurements and record the results above.
3. Plot the measured results and compare the shape of the curves with expected results.
4. Comment on the possible reasons for any differences.
5. Carefully replace all equipment in the correct places.
6. Before leaving the laboratory, complete the results, calculations and comments. Hand in your report. [If you do not complete the full report on the day, ask your tutor to sign and date this page, and hand in your report within 7 days].