

Summary

The purpose of this assignment was to investigate the performance of two different electromechanical drive systems. The first comprised of a variable frequency inverter driving an induction motor and load, and the second was a full-wave, half-controlled, rectifier bridge with a by-pass diode driving a dc motor and load.

A series of current, voltage and waveform measurements were taken in order to produce a series of graphs to show the performance data for each system.

Together with the results obtained, it will be shown that there are advantages and disadvantages for both systems, and which system is chosen will depend on the particular application.

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Introduction

Background theory.

Variable frequency inverters.

An inverter is the opposite of a rectifier - it converts dc power into ac power but at a controllable rate (voltage/current or frequency). The output voltage of the inverter can be controlled by the use of pulse width modulation (PWM). This output is not a perfect sine wave but an approximation created from the 'chopping' of the rectified ac input.

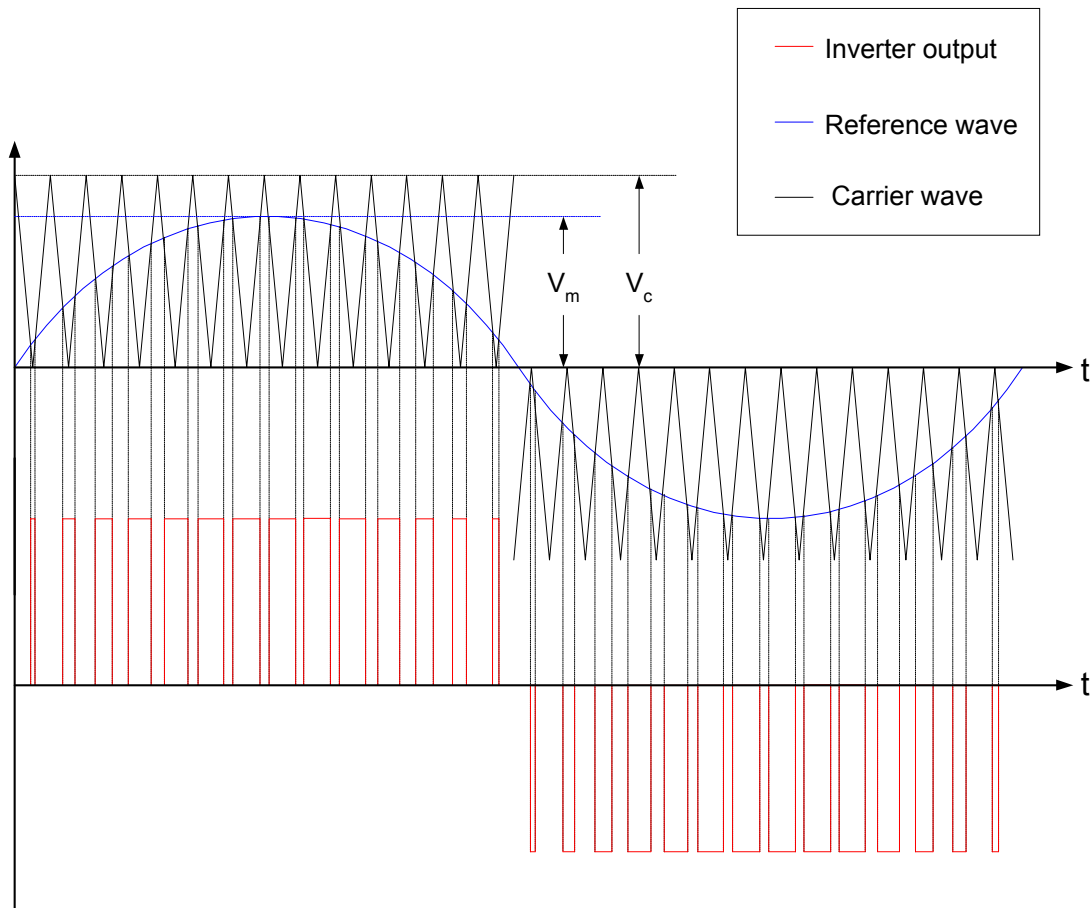


Fig.1 PWM voltage waveform

The output voltage from the inverter is controlled by the duty cycle of pulses, so as the reference wave reaches its maximum value, the 'on' pulses become larger. The reference waveform is of amplitude V_m and frequency f_m , and the carrier wave is of amplitude V_c and frequency f_c . The output of the inverter is switched 'on' when these two waveforms intersect.

There are two control parameters that control the output voltage, the chopping ratio and the modulation index. The modulation index, $M (V_m/V_c)$, gives the width of the pulse and therefore the RMS output voltage. The chopping ratio, $N (f_c/f_m)$, gives the number of pulses in each half cycle. The chopping ratio is usually kept high in order to keep the harmonic frequencies of the output waveform high. This allows for easier filtering and torque pulsations are reduced, resulting in smoother rotation.*

* [Power Electronics and Motor Control, 2nd edition, Page 492, Shepherd, Hulley and Liang, Cambridge University Press, 1995]

DC motor and power electronic controller.

The power electronic controller for the DC motor consists of a full-wave, half controlled bridge rectifier with a by-pass diode. This enables good controllability and higher system efficiencies to be achieved.

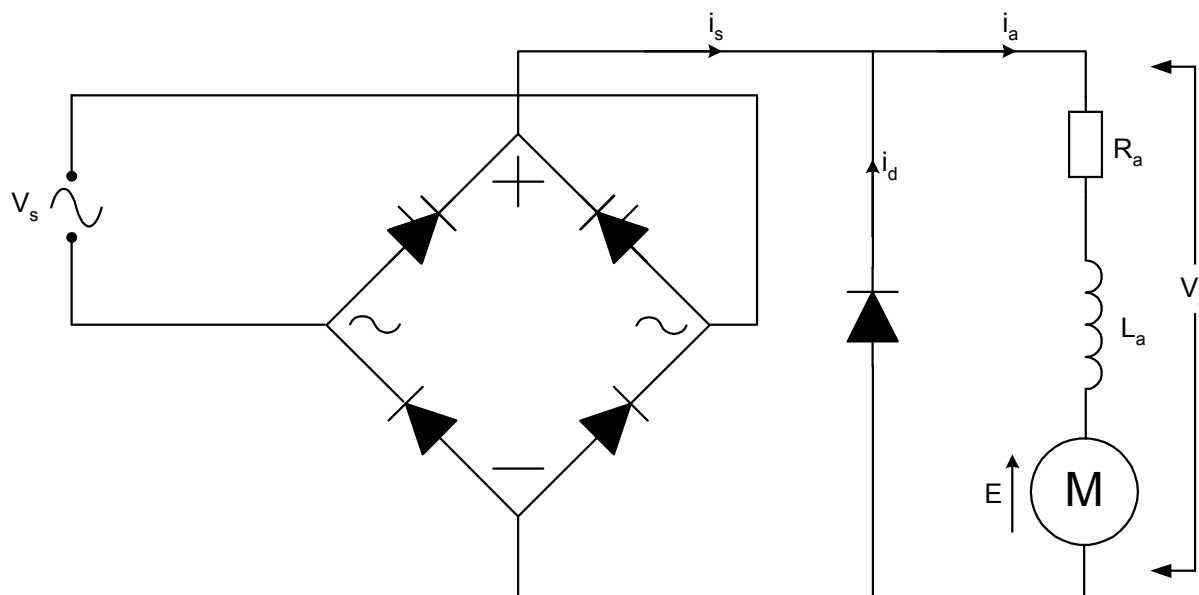


Fig.2 DC motor supplied via half controlled single phase bridge with flywheel diode

In theory the speed of a DC motor could be adjusted by placing a large variable resistor in series with the armature winding but this would be inefficient due to the large losses and no effective speed regulation. A better method of control is to use the half controlled bridge where by varying the firing angle of the thyristors, the voltage supplied to the motor can be reduced or increased, and therefore the speed of the motor can adjusted accordingly.

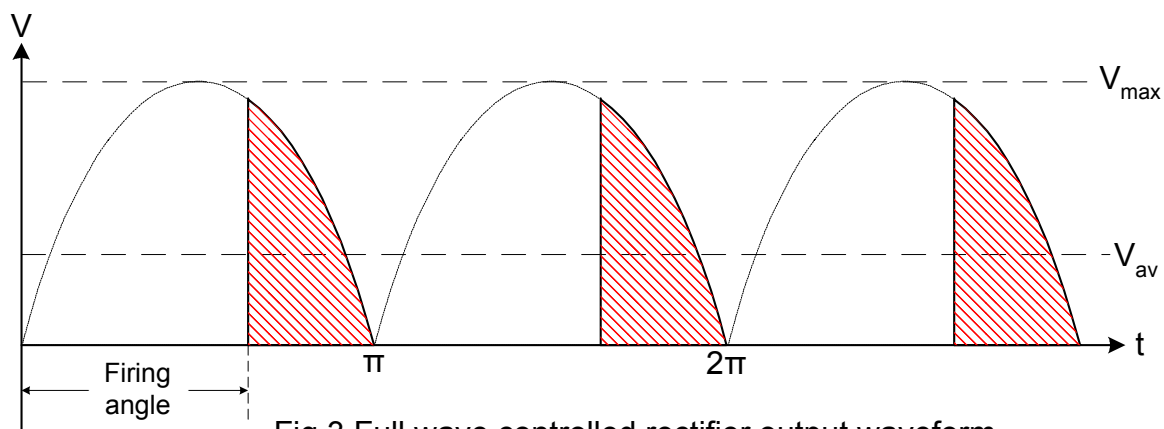


Fig.3 Full wave controlled rectifier output waveform

The motor itself produces an emf that needs to be included when calculating the average out put voltage, such that the waveform appears so:

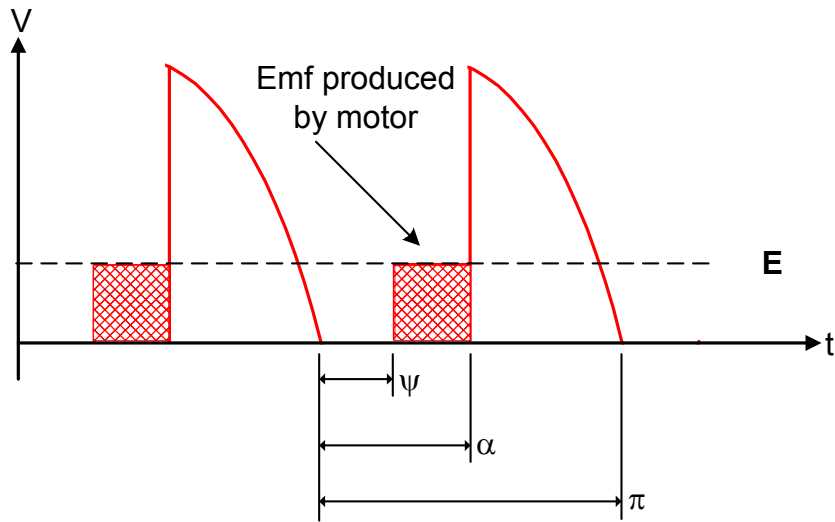


Fig.4 Voltage waveform for DC motor with power electronic controller

Figure 1

The average value for the output from this circuit when driving a dc motor is given by the equation:

$$V_{av} = \frac{1}{\pi} \left[\int_{\psi}^{\alpha} E d\theta + \int_{\alpha}^{\pi} V_m \sin\theta d\theta \right]$$

Where:

E=the emf produced by the motor
 α =The firing angle of the thyristors

Objective

The circuits were connected as shown in the diagrams below, and a series of measurements were taken in order to obtain the working characteristics of both the systems.

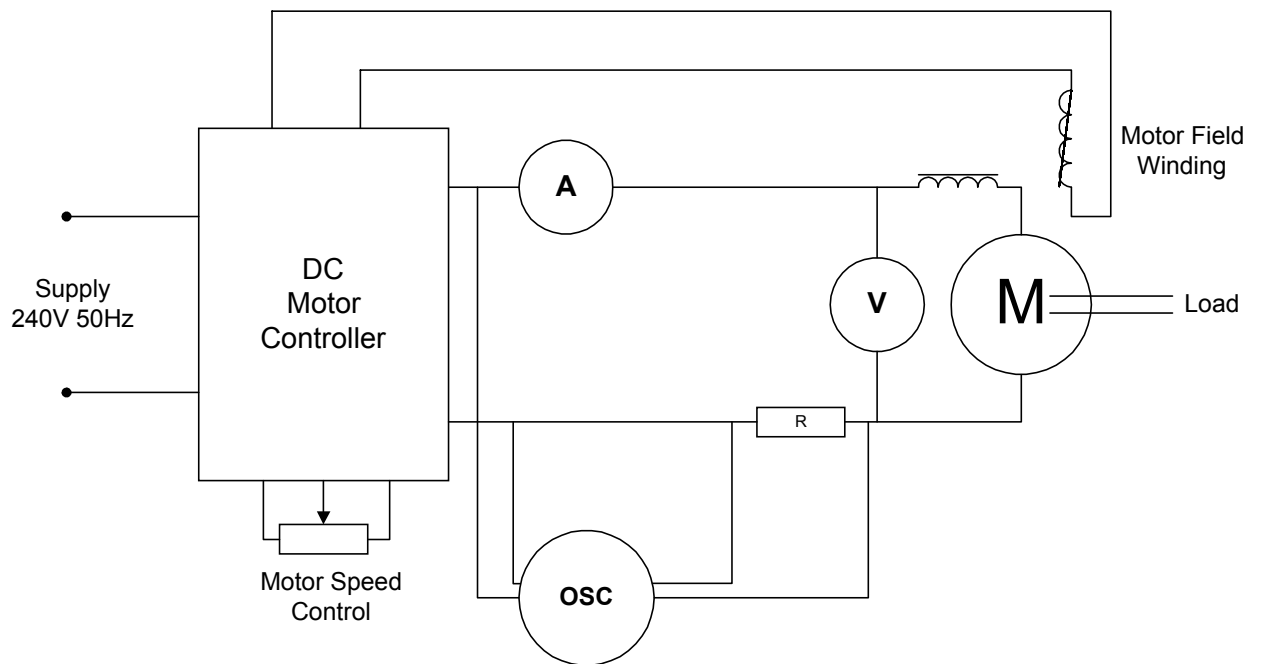


Fig.5 Circuit diagram for DC motor with power electronic controller

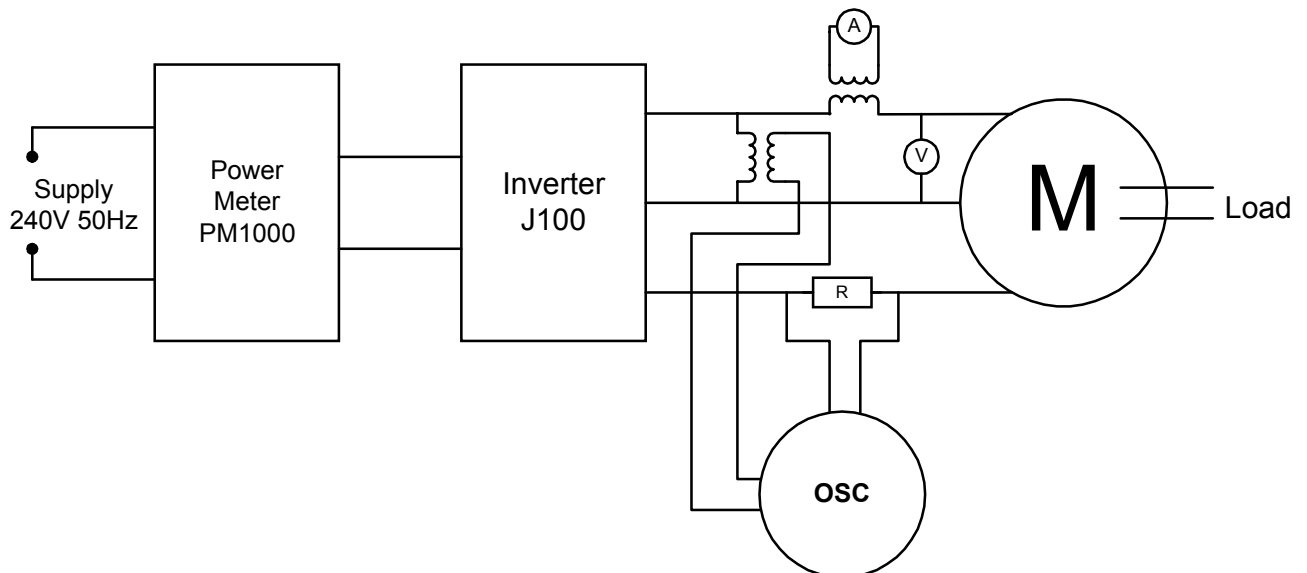


Fig.6 Circuit diagram for induction motor with variable frequency inverter

Results

Tables and calculations

Induction motor with variable frequency inverter

Inverter Frequency (Hz)	Inverter Voltage (V)	Motor Speed (RPM)	Motor Current (A)
5	24	136	0.83
6	27	168	0.82
7	30	197	0.80
8	34	227	0.78
9	38	254	0.76
10	42	283	0.75
11	46	313	0.74
12	50	345	0.72
13	54	373	0.71
14	58	403	0.70
15	62	430	0.68
16	66	463	0.68
17	70	492	0.67
18	74	524	0.66
19	78	554	0.65
20	82	583	0.65
21	86	612	0.64
22	90	642	0.63
23	94	673	0.63
24	98	698	0.62
25	102	734	0.62
30	122	886	0.63
35	143	1036	0.63
40	164	1187	0.64
45	190	1335	0.68
50	210	1483	0.68

Fig.7 Results for induction motor (no load) with variable frequency inverter.

Torque (Nm)	Speed (RPM)	Power (W)	Power Factor	Motor voltage (V)	Motor Current (A)	Input current (Arms)
1	1153	320	-0.586	162	0.65	2.324
2	1140	478	-0.608	161	0.68	3.430
3	1127	615	-0.612	160	0.75	4.353
4	1106	777	-0.620	160	0.79	5.405
5	1091	930	-0.630	160	0.86	6.270

(Note: The negative power factor indicates that the current is lagging the voltage as would be expected in an inductive circuit)

Fig.8 Performance data results with inverter frequency set to 40Hz

DC motor with power electronic controller

Speed (RPM)	Armature Voltage (V)
100	12
200	18
300	24
400	30
500	35
600	39
700	44
800	50
900	54
1000	59
1100	65
1200	71
1300	74
1400	79
1500	84
1600	90
1700	95
1800	100
1900	105
2000	110

Fig.9 Results for DC motor (no load) with power electronic controller

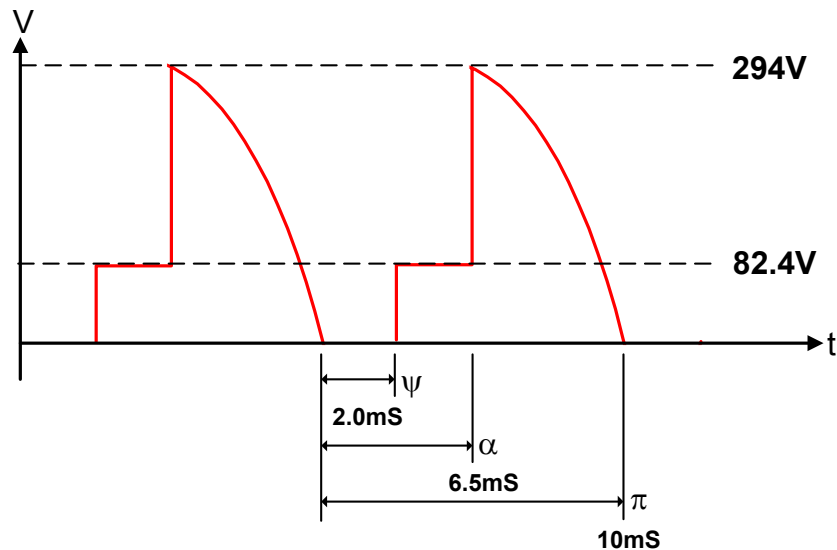
Torque (Nm)	Speed (RPM)	Input current (A)
0.75	1990	3.2
1.00	1950	3.8
1.25	1920	4.3
1.50	1895	4.7
1.75	1875	5.2
2.00	1850	5.6
2.25	1820	6.2
2.50	1800	6.6
2.75	1775	7.2
3.00	1750	7.6

Fig.10 Results for DC motor with power electronic controller (Starting speed \approx 2000RPM)

Torque (Nm)	Speed (RPM)	Input current (A)
0.75	990	3.2
1.00	975	3.6
1.25	945	4.1
1.50	925	4.6
1.75	900	5.1
2.00	890	5.6
2.25	860	6.1
2.35	845	6.4

Fig.11 Results for DC motor with power electronic controller (Starting speed \approx 1000RPM)

Calculation



From the results obtained above, we can calculate the average voltage using:

$$V_{av} = \frac{1}{\pi} \left[\int_{\psi}^{\alpha} E d\theta + \int_{\alpha}^{\pi} V_m \sin \theta d\theta \right]$$

Where:

$$\text{Firing angle, } \alpha = \frac{6.5\text{ms}}{10\text{ms}} \times 180^\circ = 117^\circ$$

$$\therefore \alpha = 117^\circ, \psi = 36^\circ, \text{ and } \pi = 180^\circ$$

$$\begin{aligned} V_{av} &= \frac{1}{\pi} \left[\int_{\psi}^{\alpha} E d\theta + \int_{\alpha}^{\pi} V_m \sin \theta d\theta \right] \\ &= \frac{1}{\pi} \left[(82.4 \times (117 - 36) \times \frac{\pi}{180}) + (240\sqrt{2} \times (\cos 117 - \cos 180)) \right] \\ &= \frac{1}{\pi} [116.49 + 185.32] \\ V_{av} &= 96.07\text{V} \end{aligned}$$

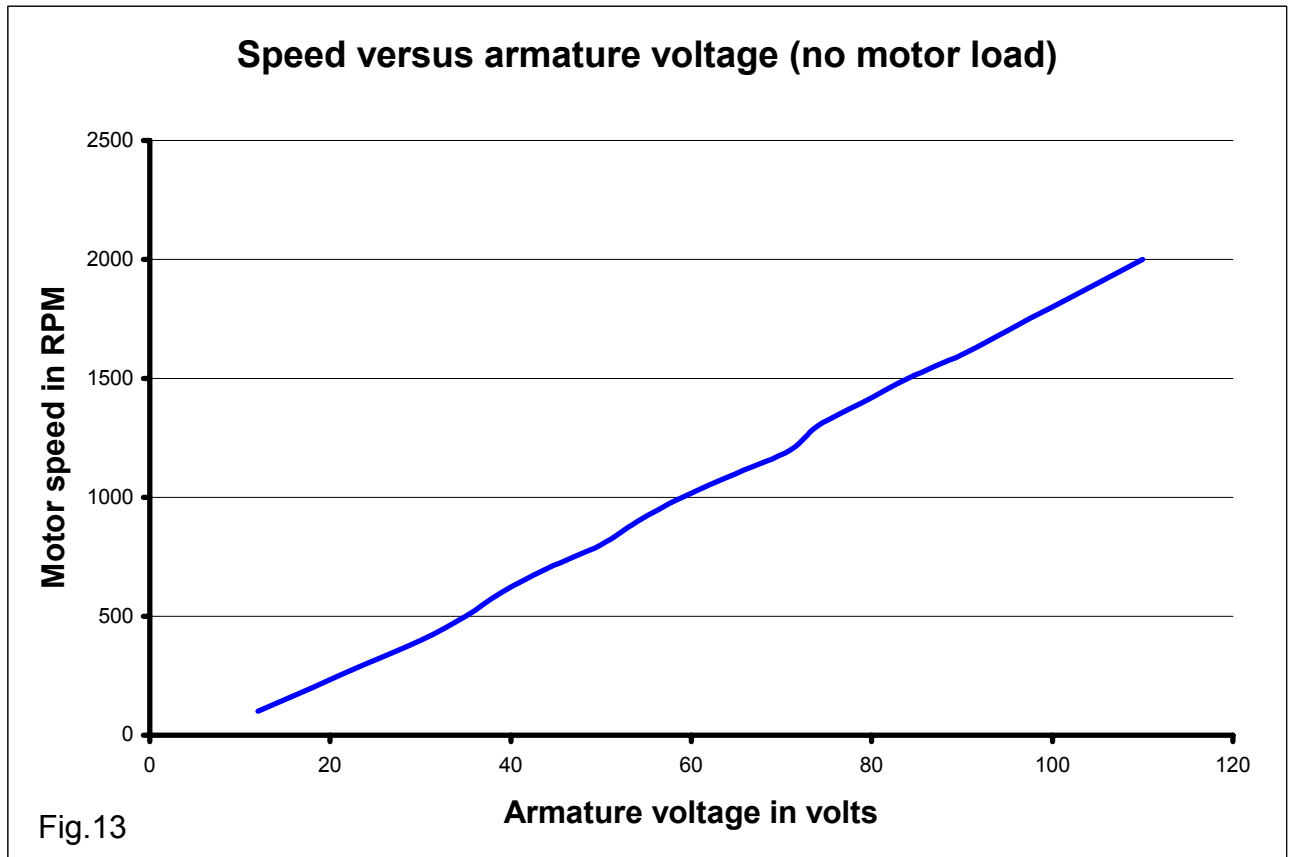
Our measured reading was 110V – inaccuracies here may be due to, among other things, the calibration of the instruments – the oscilloscope was particularly difficult to read accurately from, and the limited resolution and scale on the volt meter.

Graphs and discussion of results

DC motor with power electronic controller

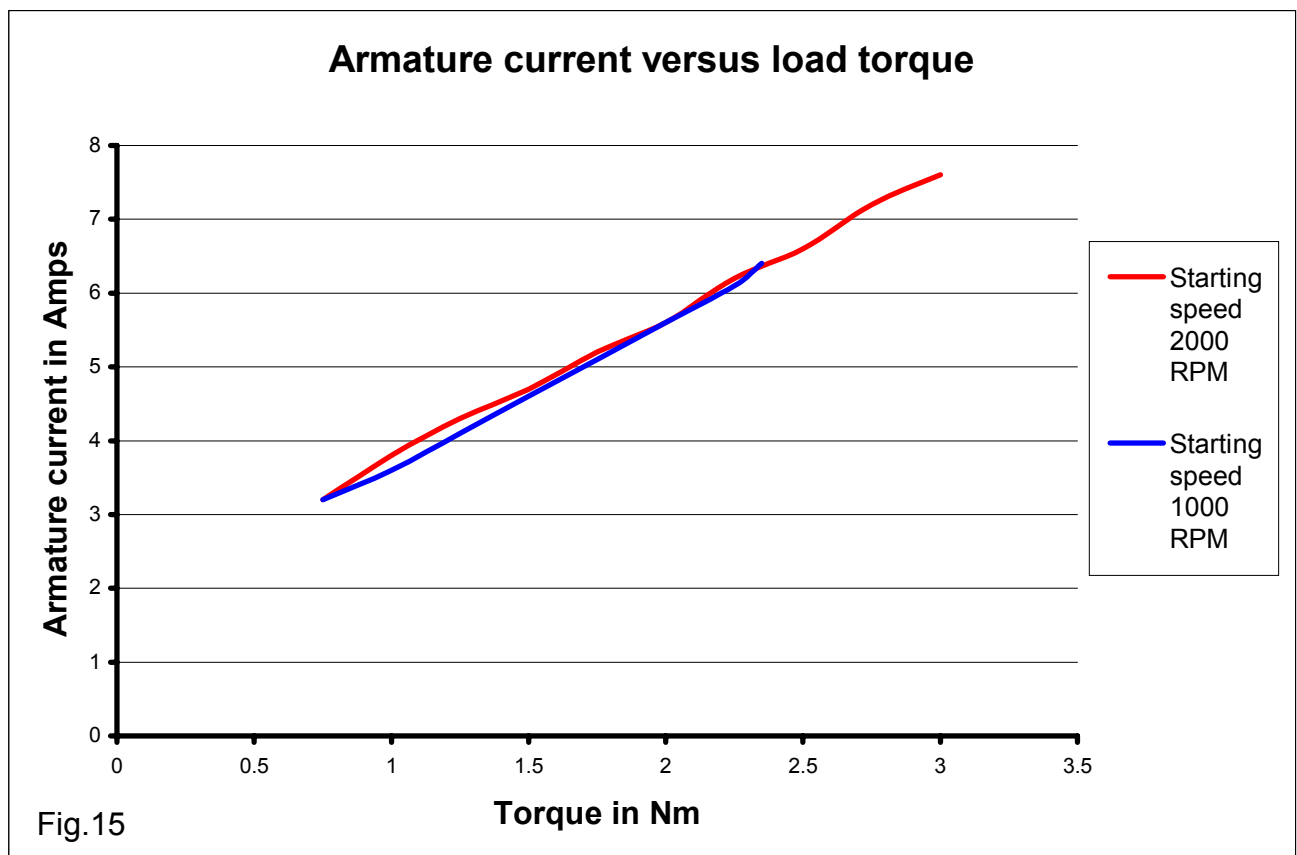
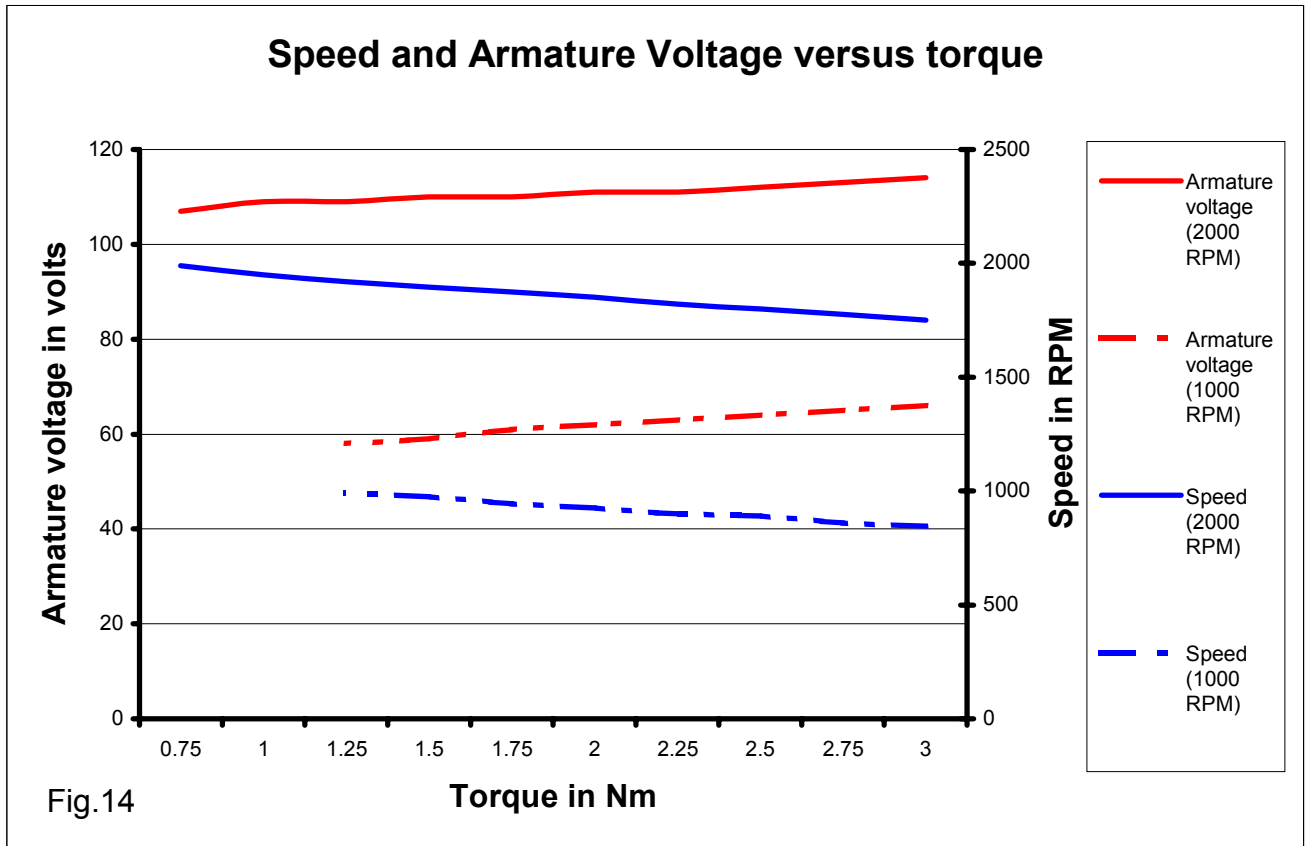
Graph.1

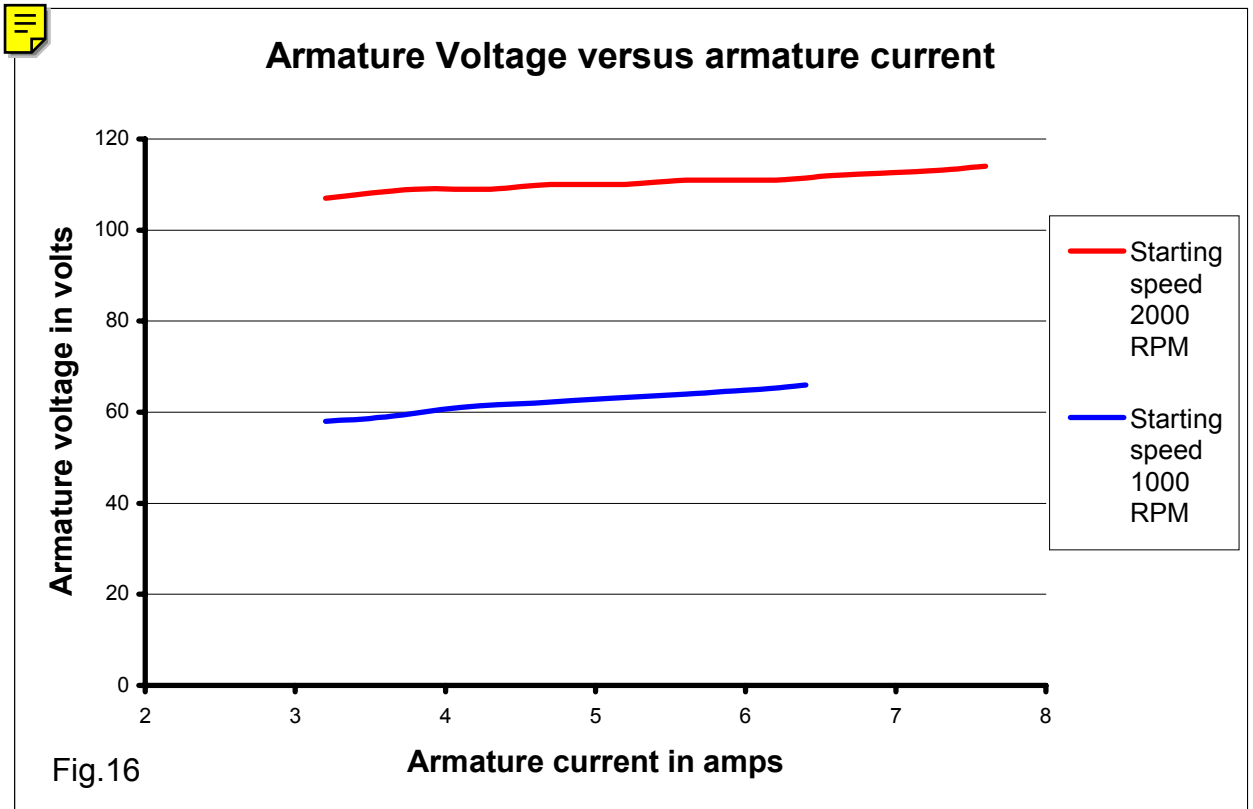
We were asked to plot the graph of speed against armature voltage, starting with a speed of about 2000 rpm and the motor on no load.



It can be seen from the above graph that as the armature voltage increases the motor speed also increases *proportionally*. It can also be seen that if the line were extrapolated, it would cross the x-axis at approximately 8-9 volts. This is caused by the static friction losses that only appear when the motor is switched on.

Starting with speeds of 2000 rpm and 1000 rpm we were asked to plot graphs of speed against torque, and armature voltage against current, to an armature current of 7.5A max with the controller unchanged from its no-load condition.

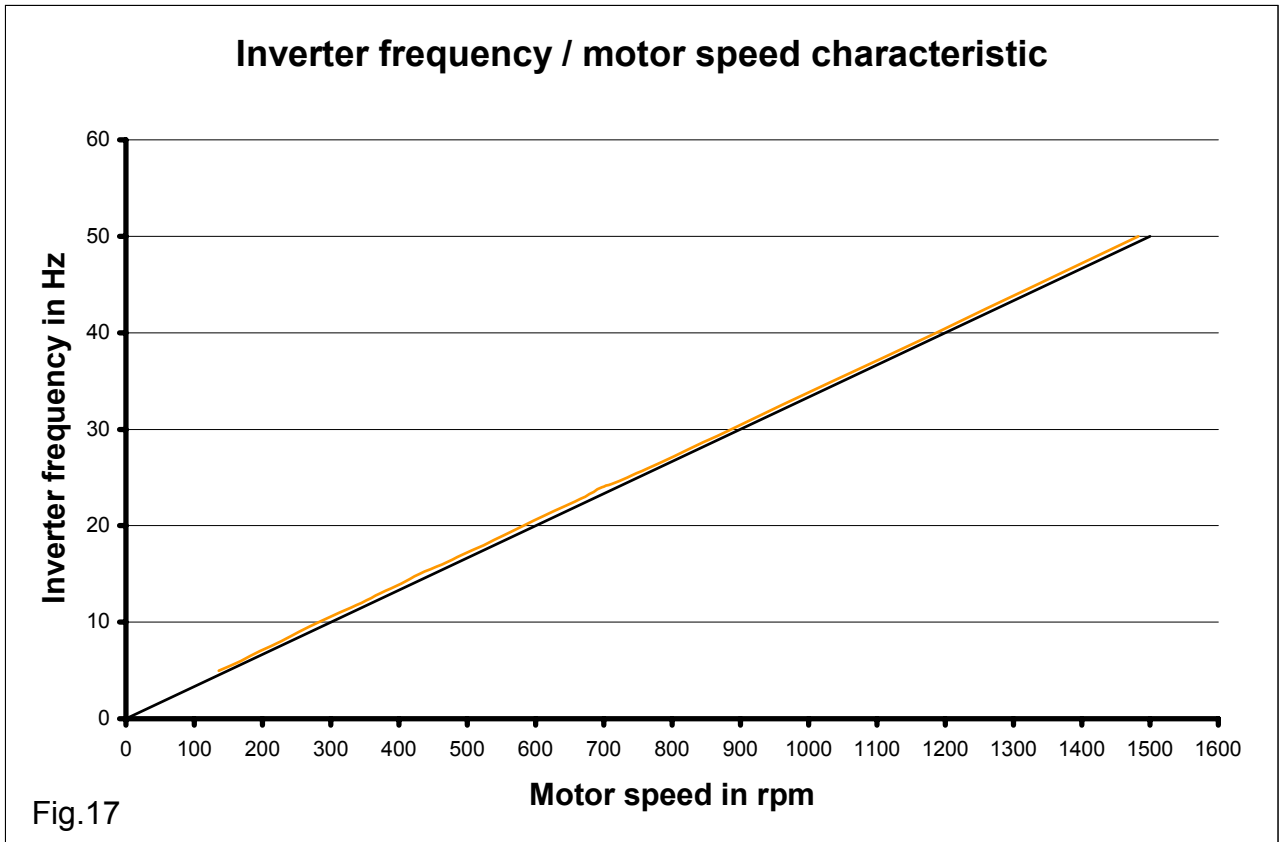




If the previous three graphs above are studied together, it can be seen that current depends mainly on load torque, and has little to do with either speed or armature voltage.

Induction motor with variable frequency inverter

We were asked to obtain a simple inverter voltage / frequency characteristic and its associated frequency / motor speed characteristic over the working range of the inverter (5-50Hz).



In this graph, I have plotted inverter frequency motor speed characteristic obtained in the experiment along with the 'ideal' characteristic. The difference between these two lines is the slip.

$$\text{Synchronous speed } n_s = \frac{f}{p} \text{ revs/s}$$

Where: f=frequency of the currents in the stator windings
p=pairs of poles

$$\therefore f = 50\text{Hz and } p = 2 \text{ (4 pole motor = 2 pairs of poles)}$$

$$\therefore n_s = \frac{50}{2} \text{ revs/s} = 25 \text{ rev/s} = (25 \times 60)\text{rpm} = 1500\text{rpm}$$

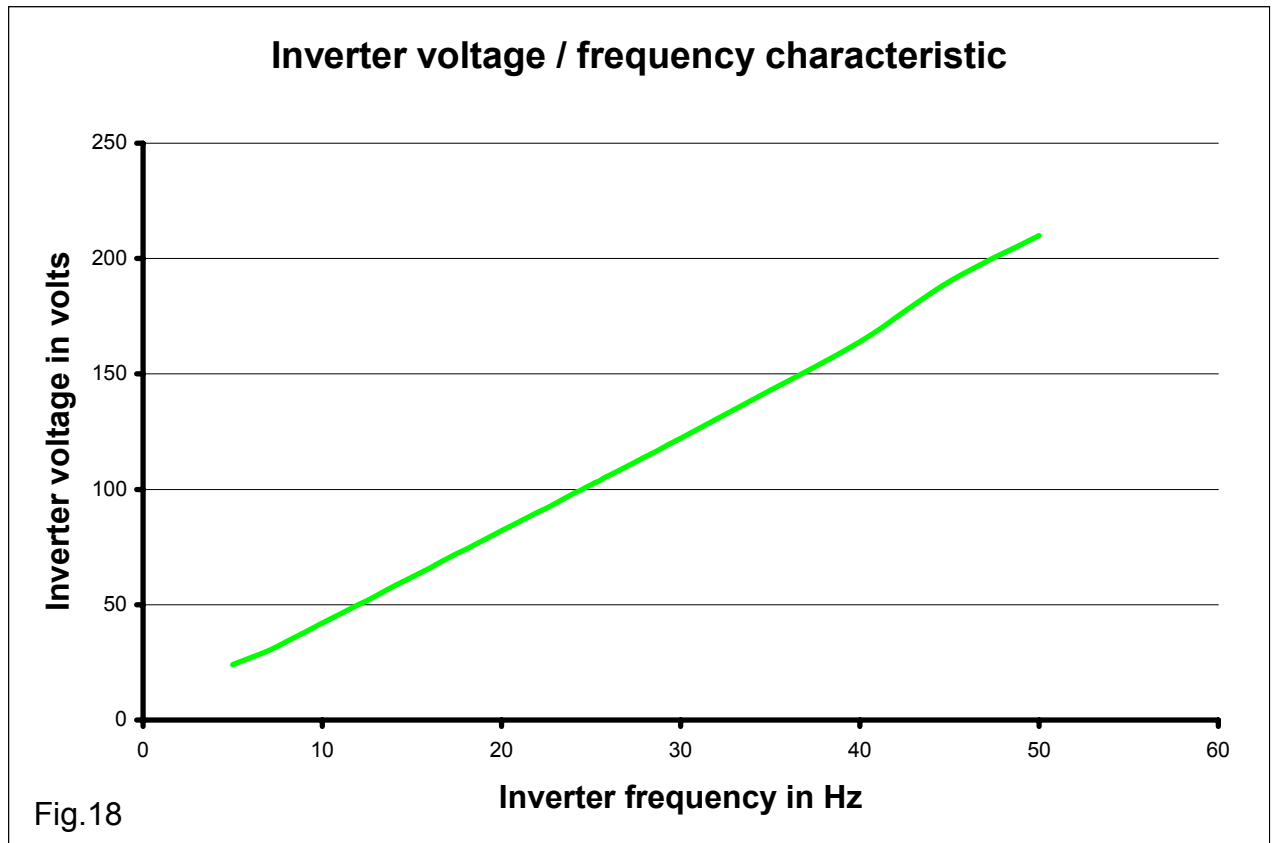
With the motor running at line frequency:

$$\text{Per unit slip } s = \left(\frac{n_s - n_r}{n_s} \right)$$

Where: n_s =Synchronous speed
 n_r =Rotor speed

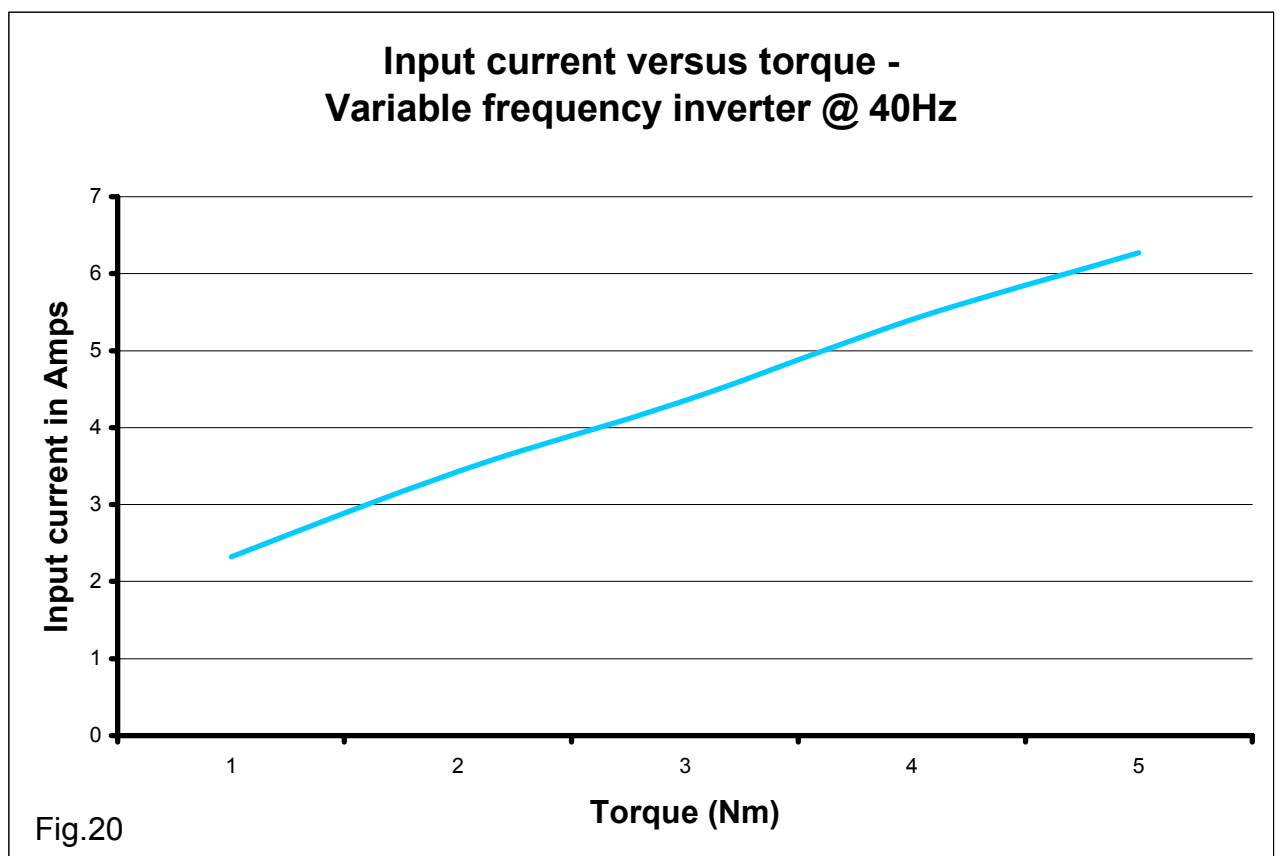
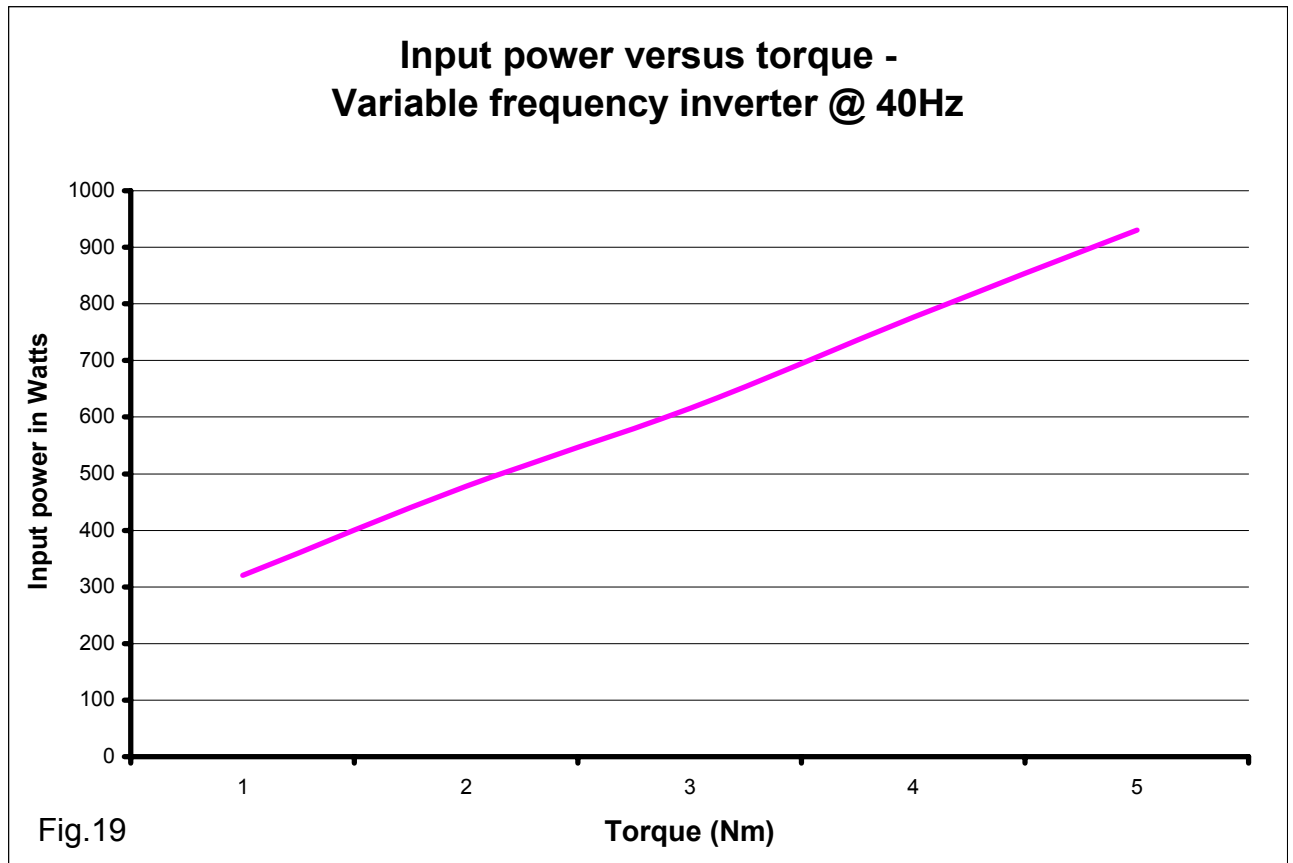
$$\therefore s = \left(\frac{1500 - 1483}{1500} \right)$$

$$\therefore s = 0.011 \text{ or } 1.1\%$$

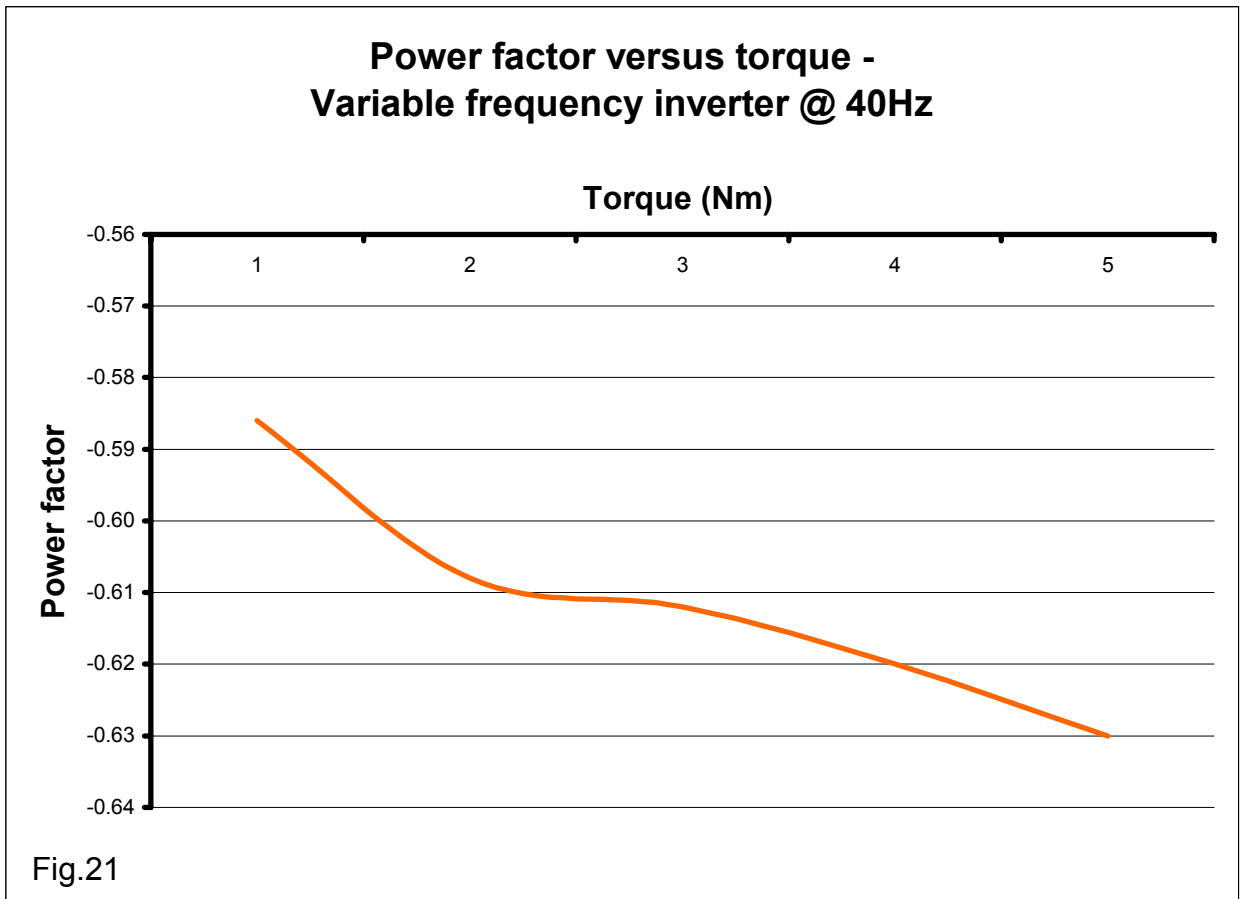


As described in its operation earlier, this graph shows that the inverter voltage is directly proportional to the inverter frequency and therefore the speed.

We were then asked to obtain performance data for the system and plot graphs of efficiency, input power factor, input current and input power versus the load torque.



With a fixed frequency, and therefore output voltage, the input current rises proportionally to the load torque. This also causes the input power to rise proportionally to the torque.

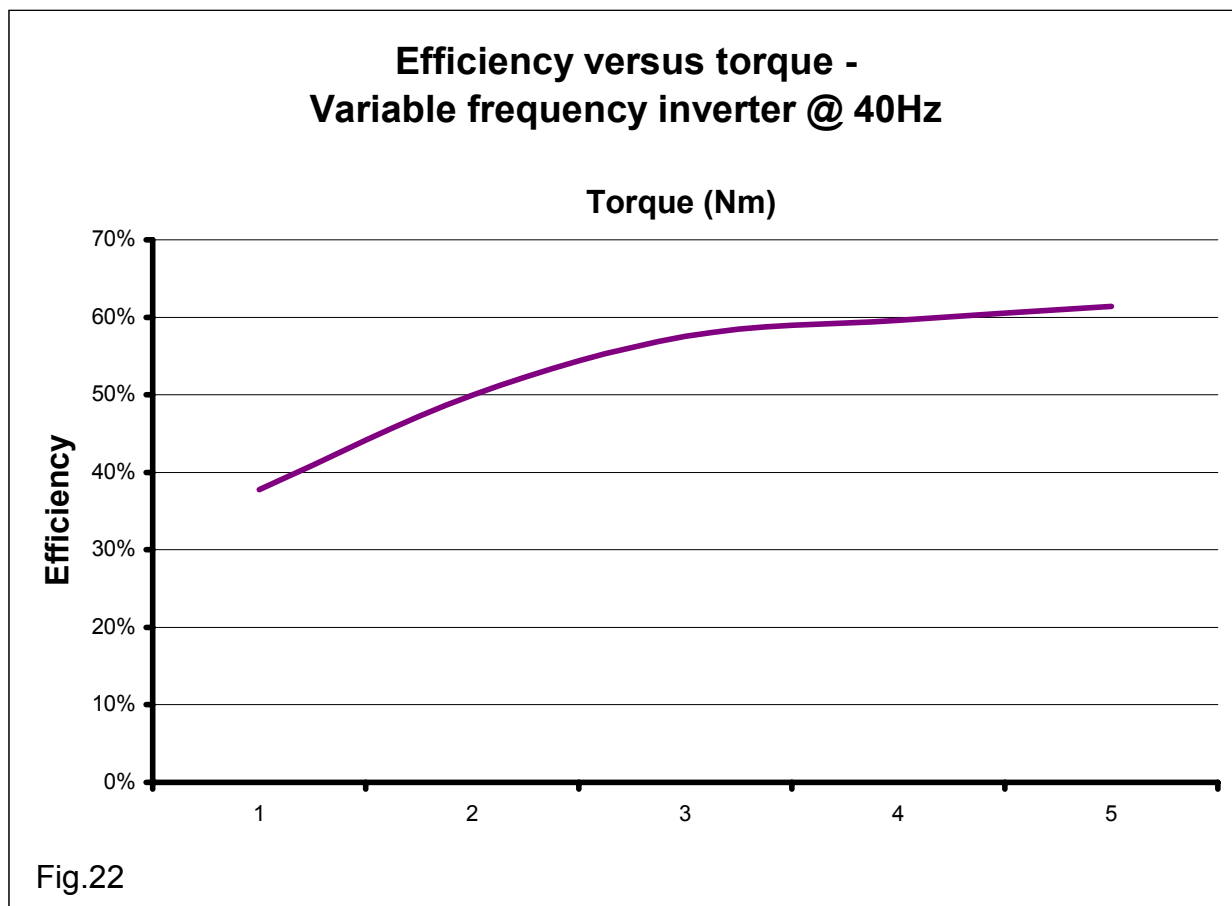


Note: The negative (lagging) power factor indicates lagging current.

AC adjustable speed drives usually operate at a lagging power factor, as verified by the graph above.

The design of the drive generally reduces the power factor still further. The low power factor of an induction motor operating from a three phase supply can be compensated for by the addition of capacitors but is not always possible when operating from a variable speed drive, and alternative methods may be required.*

* [Power Electronics and Motor Control, 2nd edition, Page 136, Shepherd, Hulley and Liang, Cambridge University Press, 1995]



This graph illustrates that efficiency was poor at low torque loads and was increasing exponentially as the load torque was increased.

Efficiency was calculated as follows:

$$\text{Gross mechanical power} = TN,$$

Where T=torque in Nm, N=Speed in radians/sec

$$\text{And } 1 \text{ rpm} = \frac{\pi}{30} \text{ radians per second}$$

$$\text{Percentage efficiency of a electrical m/c} = \frac{\text{output power}}{\text{input power}} \times 100\%$$

Torque in Nm	1	2	3	4	5
Speed in RPM	1153	1140	1127	1106	1091
Input power in Watts	320	478	615	777	930
Speed in radians per second	120.7	119.4	118	115.8	114.2
Gross mechanical power in Watts	120.7	238.7	354	463.2	571.1
Efficiency %	37.7	49.9	57.6	59.6	61.4

Fig.23 Efficiency calculations @ 40Hz

The efficiency of electrical motors at below their rated speed is usually inefficient and continuous low speed operation will often cause temperature rise problems. The efficiency of motors at their rated speed is typically 60% for one horsepower machines up to 90% for machines of several thousand horsepower.*

* [Power Electronics and Motor Control, 2nd edition, Page 134, Shepherd, Hulley and Liang, Cambridge University Press, 1995]

Conclusions

Each type of drive system has its own advantages and disadvantages. The choice of drive system depends on factors such as:

- Required speed range
- Efficiency
- Speed regulation
- Power factor
- Loading
- Running costs
- Capital outlay on equipment

DC drives	AC drives
ADVANTAGES	
Well established technology	Motor reliability
Simple, inexpensive power converter	Motor cost (size/weight)
Simple control	Environmentally insensitive
Wide speed range	Good ac power factor
Fast response	Possibly lower initial costs
DISADVANTAGES	
Motor cost (size/weight)	Complex power converter
Environmentally sensitive	Complex control
Motor maintenance	Developing technology
Poor power factor (for ac rectified supplies)	*

Fig.24 Advantages/disadvantages of AC/DC drives

The variable frequency inverter provides a better, more efficient method, of speed control for 3 phase induction machines. The synchronous speed of the induction motor is proportional to the input frequency and the machine operates with only a small change in speed (and therefore slip) between no load and full load.

The efficiency is also better for a dc motor with power electronic drive and creates better controllability. The mechanical alternative to these controllers is a gearbox, but this will bring its own losses to the system, requires regular maintenance and is not so infinitely variable as a power control system.

Rather than the choosing a drive system, it would perhaps be better to decide the motor choice first. An ac motor has the advantage that it is a much simpler construction and therefore has a correspondingly lower cost. Maintenance is simpler with no need to replace brushes or undercut armatures. The lack of carbon brushes within the motor also means there are no sparks, so the motor is far more intrinsically safe when working in hazardous environmental conditions. The makeup of the ac induction motor means that all the power supplied to the motor runs through the stator located on the 'outside' of the motor housing which allows for better/easier cooling to be provided.

The advantages of the dc motor are that it is cheap to buy initially and that the control technology is well established and proved. The motor itself has a good torque/speed characteristic, with good low speed performance – the motor could exert torque without actually rotating. This characteristic may be required in an industry such as the newspaper printing where the printing line may stop but the paper needs to be 'held' - the dc motor would be able to hold the paper under tension without feeding.



* [Power Electronics and Motor Control, 2nd edition, Page 148, Shepherd, Hulley and Liang, Cambridge University Press, 1995]

Additional comments.

For the experiment using the induction motor with variable frequency inverter we were unable to complete a second set of results at a frequency other than 40Hz, due to lack of time. It was also noted that the inverter should provide a boost at low speeds, shown by a lift in the invert voltage/frequency characteristic at low frequency, but we were unable to find such a lift – this could be attributed to the fact that the inverter is a programmable device and was not set correctly to provide such a boost.

For the experiment using the dc motor with power electronic controller, we were unable to obtain system efficiency due to a lack of relevant readings.

Errors may occur from the following factors:

- Calibration and resolution of the equipment used to make the measurements
- The temperature coefficients of the components – the characteristics of the components will change the longer the circuit is energised.
- Ambient conditions – temperature and humidity can affect the instruments and the circuit itself
- Connections to the circuit itself – the way the components were connected may increase the overall resistance of the circuit.
- Human error when taking readings from instruments.
- Mathematical errors due to 'rounding up' in calculations – these errors are further compounded if the figure is used to calculate further values.

Some or all of these errors may occur and as with mathematical errors will compound to give increased errors.

Appendix

Sources of reference material

The following were used as sources of reference material within this report:

- Lecture notes – Dr.M.Lewis, University of Huddersfield
- Power electronics for technology, A.Ahmed, Prentice-Hall
- Power electronics, C.W.Lander, McGraw-Hill
- Power electronics and motor control, Shepherd, Hulley and Liang, Cambridge university press

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