INSTRUMENTATION AND CONTROL

TUTORIAL 2 – ELECTRIC ACTUATORS

This is a stand alone tutorial on electric motors and actuators. The tutorial is of interest to any student studying control systems and in particular the EC module D227 – Control System Engineering.

On completion of this tutorial, you should be able to do the following.

- Describe the advantages and disadvantages of electric actuation.
- Describe how a.c. motors are used for actuation.
- Explain how d.c. motors are used for actuation.
- Explain the basic principles of stepper motors.
- Explain how linear motion is obtained.
- Explain in some detail the principles of various types of d.c. servo motors.

If you are not familiar with instrumentation used in control engineering, you should complete the tutorials on Instrumentation Systems.

In order to complete the theoretical part of this tutorial, you must be familiar with basic electrical science.

1. INTRODUCTION

Electrically actuated systems are very widely used in control systems because they are easy to interface with the control systems which are also electric and because electricity is easily available unlike fluid power which require pumps and compressors.

The advantages of electric systems are

- Electricity is easily routed to the actuators; cables are simpler than pipe work.
- Electricity is easily controlled by electronic units
- Electricity is clean.
- Electrical faults are often easier to diagnose.

The disadvantages of electric actuators are

- Electrical equipment is more of a fire hazard than other systems unless made intrinsically safe, in which case it becomes expensive.
- Electric actuators have a poor torque - speed characteristic at low speed.
- Electric actuators are all basically rotary motion and complicated mechanisms are needed to convert rotation into other forms of motion.
- The power to weight ratio is inferior to hydraulic motors.

There are three types of motors used in control applications.

- A.C. motors.
- D.C. motors.
- Stepper motors.

2. A.C. MOTORS

A.C. motors are mainly used for producing large power outputs at a fixed speed. Typically these are 1420 or 2900 rev/min. Such motors are controlled by switching them on and off.

Increasingly, speed control is being used with A.C. motors on applications such as pumps where it is found to be more economical to control the flow rate by changing speed rather than by opening or closing a pipe line valve. Speed control is achieved electronically by varying the frequency or by chopping the power supply.

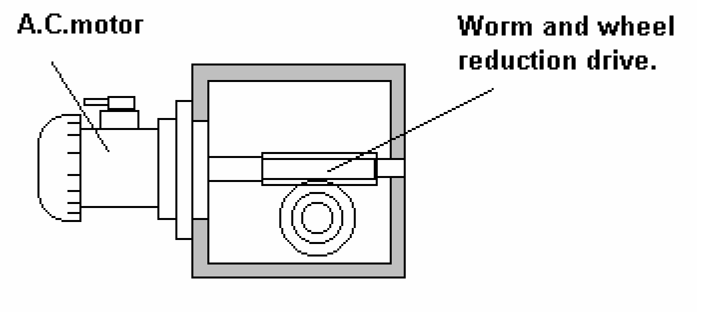


Figure 1

These motors are usually geared down in order to produce a greater torque and increase the control range. They may also have the rotation converted into linear movement by a lead screw mechanism.

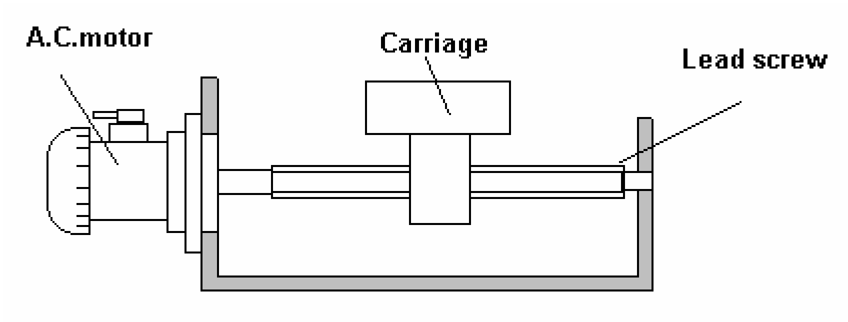


Figure 2

Lead screws are used to convert rotation into linear motion as shown. Rotation screws the carriage back and forth along the lead screw.

3. D.C. MOTORS

Direct current motors are more widely used in control applications and they are usually referred to as SERVO MOTORS. These are covered in detail later in the tutorial. The development of more powerful magnets is improving the power to weight ratio but they are still not as good as hydraulic motors in this respect. Servo motors usually have a transducer connected to them in order to measure the speed or angle of rotation. The diagram shows a typical arrangement.

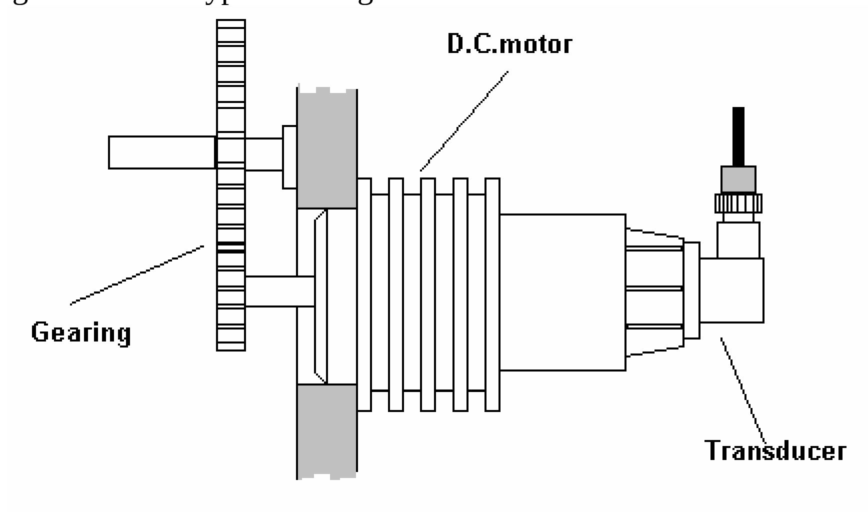


Figure 3

4. STEPPER MOTORS

Basically a stepper motor rotates a precise angle according to the number of pulses of electricity sent to it. Because there is confidence that the shaft rotates to the position requested, no transducer is needed to measure and check the position and so they are common on open loop systems. There are 3 types of stepper motor in common use and these are

Figure 4

1. The PERMANENT MAGNET TYPE.
2. The VARIABLE RELUCTANCE TYPE.
3. The HYBRID TYPE.

4.1 THE PERMANENT MAGNET TYPE.

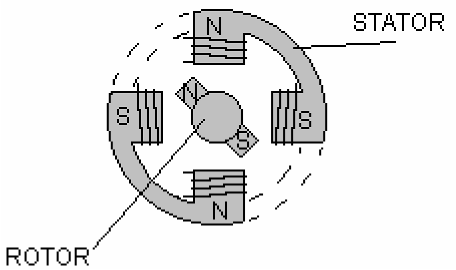


Figure 5

The rotor is a permanent magnet with a North and South poles as shown. Two pairs of poles are placed on the stator and energised to produce a pattern of N - S - N - S (starting at the top). The rotor will take up a position in between the poles due to equal and opposite torques being exerted on it.

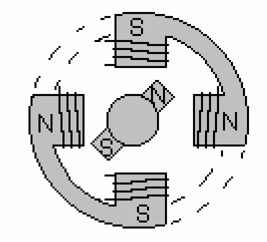


Figure 6

If the polarity of both pairs of poles are reversed the pattern will change to S - N - S - N and the rotor will flip 45^o to a new position of balance. In order to obtain more steps, more pairs of poles are used but there are only two windings. Reversing the polarity of both windings moves the rotor on one step. Stepping is produced by simply reversing the polarity.

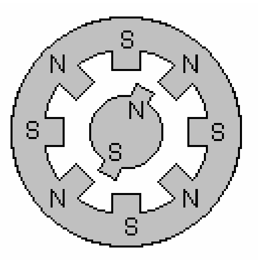


Figure 7

The rotor is held in position even when the poles are not energised. In order to obtain many steps, the poles are often stacked one behind the other and not in a single ring. The number of steps may also be increased by using a gear box on the output shaft.

4.2. VARIABLE RELUCTANCE TYPE

The rotor is constructed of soft iron with a number of teeth which are unequal in number to the number of poles on the stator. The stator has multiple poles which are energised by several separate phases. The diagram shows a system with three phases.

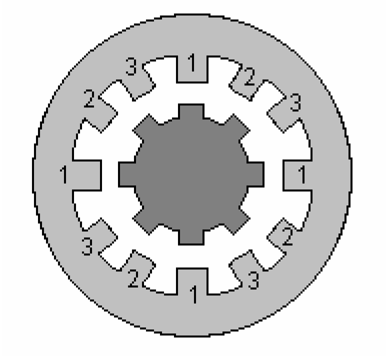


Figure 8

When a current is applied to the stator windings, the rotor aligns itself in the position of least magnetic reluctance. This position depends upon the number of phases energised.

The rotor retains very little magnetism so there is no holding torque when the current is removed.

The number of steps is given by N = SR/(S-R) where S is the number of stator slots and R the number of rotor slots.

4.3 HYBRID MOTORS

Hybrid motors are a combination of the last two types. Each pole is divided into slots as shown. The rotor has two sets of slots, one behind the other with one set offset to the other by 1/2 slot pitch. The rotor is magnetised longitudinally. This produces a high resolution.

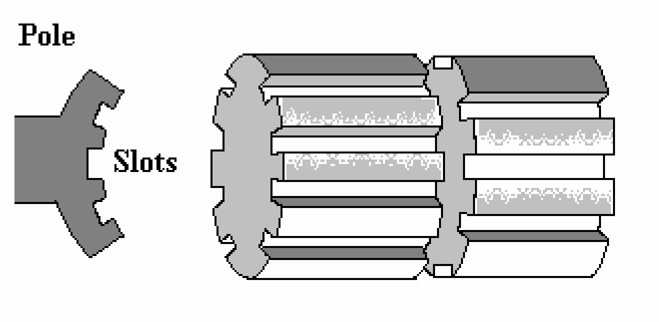


Figure 9

In general all stepper motors are controlled electronically.

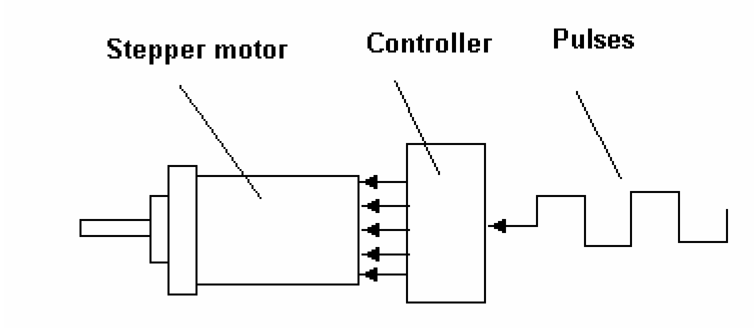


Figure 10

5. LINEAR ELECTRIC ACTUATORS

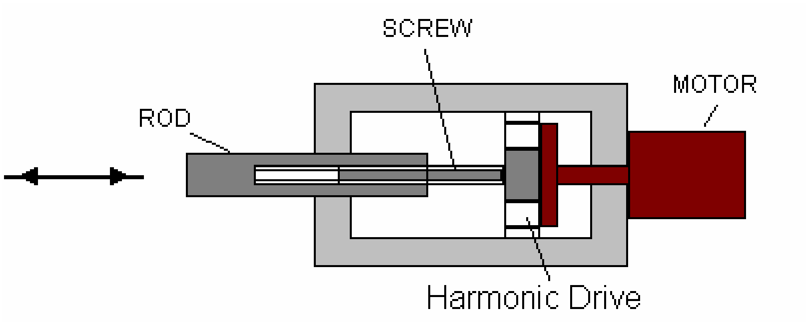


Figure 11

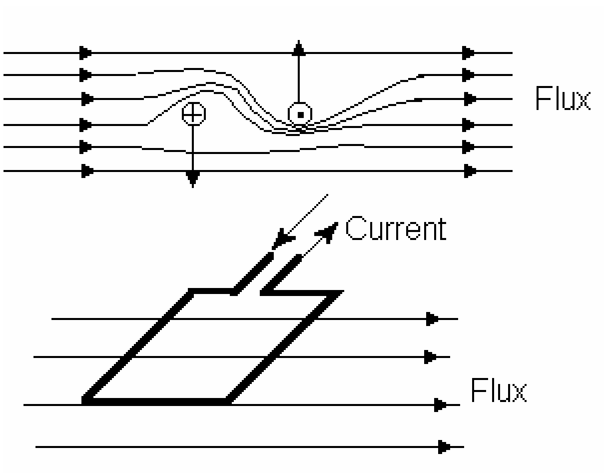
In recent years, a range of linear electric actuators have been developed to perform functions similar to hydraulic and pneumatic cylinders. These are based on a motor driven lead screw. The motors may be AC or DC. The speed of the motor is reduced with a compact gear box before driving the lead screw. Actuators have been developed with thrusts up to 15 kN and strokes up to 3 metres.

Now we will go on and examine the details of D.C. Motors.

6. DETAILED ANALYSIS OF D.C. MOTORS

The theory of electrical machines is based on two basic discoveries called the motor principle and the generator principle. In any given machine, the two go together.

6.1 THE MOTOR PRINCIPLE



When a conductor is placed in a magnetic field at a right angle to it and current flows in the conductor, a force is exerted on the conductor. The force F (Newton) is related to the flux density B (Tesla), the current I (Amps) and the length l (metres) by the formula

$$F = B \ell I$$

The flux density is the flux per unit area so $B = \phi/A$ where ϕ is the flux in Webers and A the cross sectional area of the flux path in m^2.

This force acting at a radius produces the torque T to rotate the motor. The current in the conductor is I_a.

Figure 12

For a given motor the area, lengths and radius are constant so the equation reduces to

$$\mathbf{T = k_1 \phi I_a} \quad \text{................ (1)}$$

6.2 THE GENERATOR PRINCIPLE

When a conductor moves at velocity v m/s through a flux of density B Tesla, an e.m.f is generated in the conductor such that $E = B \ell v$. This e.m.f opposes the flow of the applied current so a forward voltage is required to overcome it. This effect is produced in the conductors of motors as well as generators since the motor has moving conductors passing through a flux.

The conductor is part of a coil rotating at speed N rev/s and $v = 2\pi NR$

For a given motor in which the area and length may be considered constant, the equation becomes

$$\mathbf{E = K_2 \phi N} \text{ ....(2)}$$

6.3 GENERAL PRINCIPLES OF MOTORS

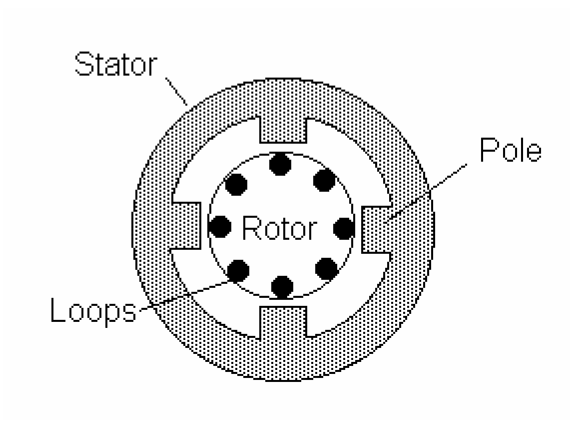


Figure 13

A basic motor is constructed of a rotor carrying the conductors in the form of a loop. The loop is placed in a flux as shown. The flux bends around the two sides and produces a torque. The loop would flip to a vertical position and no torque would be produced. In order to make the loop rotate continuously, the current must be reversed by use of a commutator. In reality, the conductor is made of many loops and the current is switched to ensure that it flows in the loop normal to the flux.

All DC motors are based on these principles. The flux may be produced by permanent magnetic poles or by separate coils called the FIELD WINDINGS. The rotor in the diagram would be called the ARMATURE. It is possible to have brushless motors and for the stator to be the armature. A typical design is the use of two pairs of poles and many loops on the rotor which are energised through the commutator.

Equation 2 may be deduced by equating mechanical and electric power. The mechanical power produced is $P = \omega T = 2\pi NT$

Where ω is the speed in radians/s and N is the speed in rev/s. Note that $\omega = 2\pi N$

E_a is the armature e.m.f. The electric power converted into mechanical power is $P = E_a I_a$

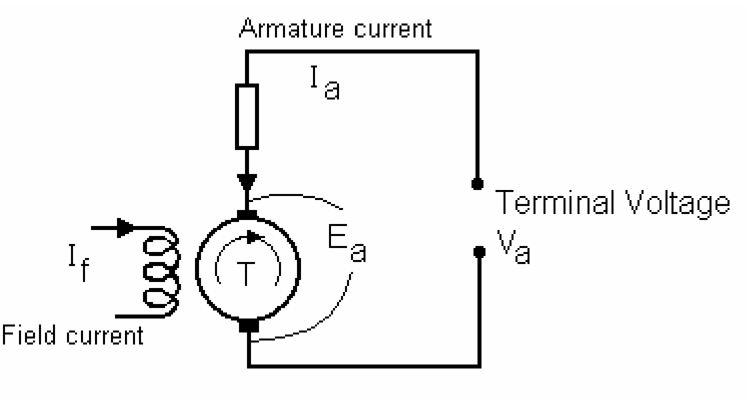


Figure 14

Equating mechanical and electric power we have $2\pi NT = I_a E_a$

$E_a = 2\pi NT/I_a$ ....(2a)

or $T = I_a E_a / 2\pi N$ ......(2b)

Since $T = k_1 \phi I_a$ we may substitute into (2a) $E_a = k_1 \phi 2\pi N = k_2 \phi N$ ......(2)

Due to losses in the armature windings, the terminal voltage V_a is given by

$E_a = V_a - I_a R_a$ ....(3)

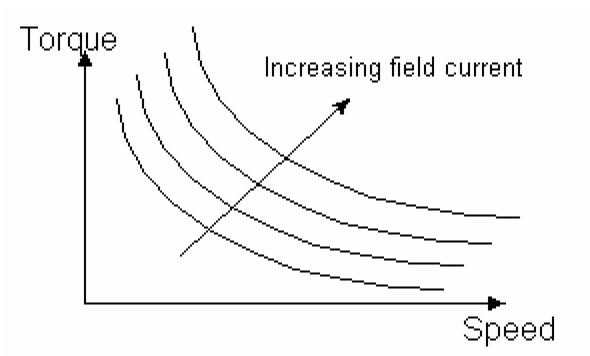
Substitute for E_a **$N = (V_a - I_a R_a)/2\pi k_1 \phi$** ....(4)

6.4 CONSTANT ARMATURE CURRENT or FIELD CONTROL

If I_a is kept constant it follows that N = constant/ϕ = constant/I_f

Since $T = k_1 \phi I_a$ and for constant I_a it follows that T = constant x ϕ

Hence N= constant/T



It follows that the torque and speed may be controlled by varying the field current. This has an advantage that a relatively large power may be controlled by a small field current and the power amplifier needed in the control circuit is relatively small. The diagram shows the relationship between torque and speed for constant field current.

Figure 15

6.5 CONSTANT FIELD CURRENT OR ARMATURE CONTROL

In this case the field current is maintained constant or a permanent magnet is used to produce constant flux.

Since $E_a = 2\pi NT/I_a$ (equation 2a) and $T \propto \phi I_a$ then $E_a \propto N\phi$

If ϕ is constant then $E_a = 2\pi N K$ ....(5) and $N = E_a/2\pi k$

Substituting for N in equation (2a) gives $T=kI_a$ hence $T = k_tI_a$

or $I_a = T/k_t$ ....(6)

Equating (3) and (5) we have

$E_a = V_a - I_aR_a = 2\pi NK = K_e N$

Substitute (6) for I_a and

$V_a - TR_a/k_t = N K_e$

$T = (V_a - Nk_e)k_t/R_a$

$\mathbf{T = C_1V_a - C_2N}$ ....(7)

or

$\mathbf{V_a = C_3T + C_4N}$............................(8)

These are the equations commonly used to explain the steady state characteristic of a DC motor with armature control.

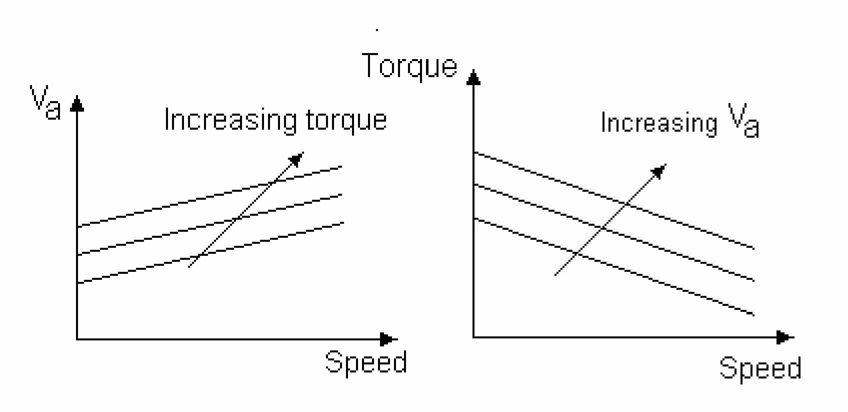


Figure 16

The diagrams above show equation 8 plotted for constant T and equation 7 for constant V_a.

6.6 MIXED CONTROL

So far you have studied motors with separate field and armature windings and looked at the characteristics of these motors.

We will now study the characteristics of various motor configurations of the type mainly used on large D.C. Machines. In the previous work it was shown that

$$\mathbf{V = E_a + I_a R_a \qquad E = k_1\phi 2\pi N = kN\phi \qquad T = K_1 \phi I_a}$$

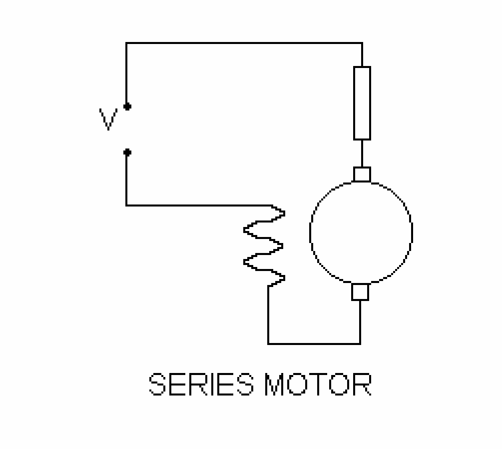
E_a is the back e.m.f on the armature, ϕ is the flux per pole, T is the torque and N the speed (rev/s).

The Mechanical Power output of the motor is less than the Electrical Power at the terminals because of losses. The efficiency of the motor is defined as

η = Mechanical Power/Electrical Power

Mechanical Power = $2\pi NT$ and Electrical Power is terminal Volts x Amperes.

6.7 SERIES MOTOR



In this case, the field winding is in series with the armature. The same current flows through the armature and the field winding.

Equating mechanical and electrical powers we have $P = 2\pi NT = E_a I_a$

Rearranging we have $T = E_aI_a /2\pi N$

If the electric power is constant, E_aI_a are constant so
$T = \text{Constant} /N$

Figure 17

In this case for constant electrical power the relationship between torque and speed is inversely proportional.

The torque - speed characteristic shows that at low torque (no load conditions) the motor is liable to over speed and become damaged.

At low speed there is a high torque (starting torque) which is ideal for servo applications.

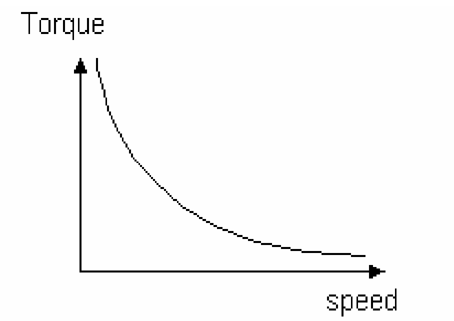


Figure 18

WORKED EXAMPLE No.1

A series wound motor produces 30 kW of mechanical power and is connected to a 250 V supply. The motor runs at 800 rev/min when under load. The load is reduced to 200 N m and a resistance of 0.5 Ω is connected in series with the motor. Assuming no energy losses, calculate the speed.

SOLUTION

Initial conditions.
Motor current I = Power/Volts = 30 000/250 = 120 A
Mechanical power = $2\pi NT/60$ = 30 000 W
T = (30 000 x 60)/(2 π x 800) = 358 N m.
$T = K_1\phi I_a$ Since flux is proportional to current and the field current is the armature current then
$T = K I_a^2$
$358 = K \times 120^2$ K = 0.02486

Final conditions. Use the same value for K. $T = 200 = 0.02486\, I_a^2$
I_a = 89.7 Amps Input Power = V I_a = 250 x 89.7 = 22 423 Watts

Loss in 0.5Ω resistance is $I_a^2 R = 89.7^2 \times 0.5$ = 4 023 W
Useful Power = 22 423 - 4 023 = 18 400 Watts = $2\pi NT/60$

N = (18 400 x 60)/(2π x 200) = 878.5 rev/min

SELF ASSESSMENT EXERCISE No.1

1. A series motor is connected to a 500 V supply. The motor power output is 10 kW at 1200 rev/min. The efficiency of the motor is 92 %.

   Determine the current and torque. (21.74 A and 79.58 N m)

2. A series motor has an armature resistance of 0.5 ohms and a field resistance of 1 ohm. It is connected to a 300 V supply and draws 50 Amperes from it. The motor runs at 1000 rev/min. The flux per pole is 0.03 Wb. The current is dropped to 25 Amperes and the flux per pole drops to 0.02 Wb. Determine the speed of the motor under these conditions. (1 750rev/min)

6.8 SHUNT MOTOR

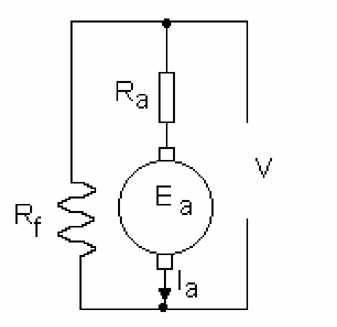


Figure 19

In this case the field winding is connected across the supply. Since the field current is constant, the characteristics are those of an armature controlled motor covered earlier.

$E_a = V - I_aR_a$

$T = k_1\phi\, I_a$ so $I_a = T/\phi k_1$

$E_a = V - TR_a/\phi k_1 = k\, N\phi$ but ϕ is constant so everything is a constant except T and N so for constant electrical power this reduces to

$$T = C_1 - C_2 N$$

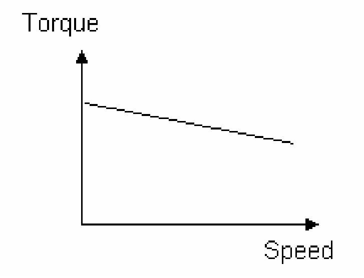


Figure 20

This shows that at zero speed the starting torque is C_1 and as speed increases, the torque drops off. The ideal Torque - Speed characteristic is as shown. In reality the line is curved down due to other effects not considered.

WORKED EXAMPLE No.2

Part 1. A D.C. motor is shunt wound and is supplied with 500 V. The armature resistance is 1.0 Ω and the field winding has a resistance of 500 Ω. When running with a torque of 100 Nm, the motor takes 21 Amps. Determine the speed of the motor.

SOLUTION

The field is connected across the supply. The current taken by the field winding is

$$I_f = 500/500 = 1 \text{ amp}$$

The current taken by the armature is hence 21 - 1 = 20 amps.

$E_a = V - I_aR_a = 500 - 20x1 = 480$ V

Electric power converted into mechanical power = $E_aI_a = 480 \times 20 = 9600$ Watts

Assuming the conversion process is 100% the Mechanical power = 9600

$2\pi NT = 9600$

$N = 9600/(2\pi T) = 9600/(2\pi \times 100) = 15.27$ rev/s or 916.6 rev/min

Part 2. The field current remains unchanged and the torque is increased to 120 Nm. Determine the new speed.

SOLUTION

Torque = $K_1\phi\, I_a$ Since the flux is constant then $T = KI_a$

From the fisrt set of data we have 100 = K x 20 so K = 5

For the second set of data we have $120 = kI_a = 5 \times I_a$

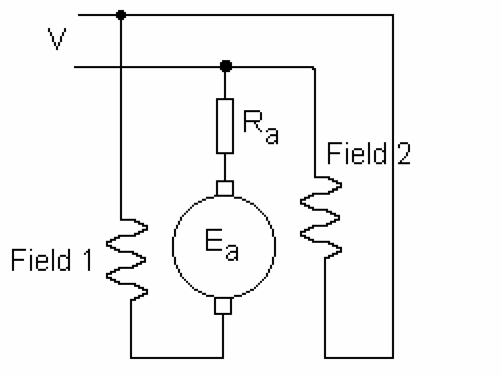
I_a = 24 amps.E = 500 - 24 x 1 = 476 V

Electric Power = 476 x 24 = 11 424 Watts

Equating to mechanical power 11 424 = $2\pi NT = 2\pi N \times 120$

$N = 11\,424/(2\pi \times 120) = 15.15$ rev/s or 909 rev/min

6.9 COMPOUND MOTOR



The compound motor is a cross between the other two with both a parallel and series field winding. For constant electric power, the Torque - speed characteristic is between that of the other two.

Figure 21

SELF ASSESSMENT EXERCISE No.2

1. A 250 V, 30 kW series motor runs at 800 rev/min on full load. A resistance of 0.5 Ω is connected in series with the motor and an output torque of 200 Nm is produced. Calculate the speed at this condition. It may be assumed that there are no energy losses and that the field flux is directly proportional to current.

   (Ans. 878.5 rev/min)

2. The armature of a 200 V d.c. motor has a resistance of 0.4 Ω. The no load armature current is 2.0 A. When a torque is applied, the armature current increases to 50 A, and the speed is 1200 rev/min. Find the no load speed stating any assumptions made.

   (Ans.33200 rev/min)

3 A 230 V d.c. motor has a separate field coil with a constant current of 2.2 A. The armature resistance is 0.15 Ω. The motor was tested with no load applied to the shaft. The armature current was found to vary with armature voltage as follows.

Current	4.9 A	4.5 A	4.0 A	3.6 A
Volts	230	180	130	80

The speed at 230 V was 1150 rev/min. Determine the speeds at the other voltages.

(Ans. 890, 650, 400 rev/min)

4. The armature rersistance of a 250 V d.c. shunt wound motor is 0.7 Ω and the armature current is 2.0 A when operating under no load conditions. A torque is then applied to the shaft and the armature current rises to 60 A and the speed falls to 1000 rev/min. Determine the no load speed.

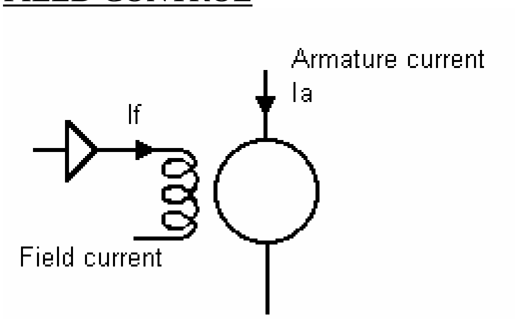
   (Ans. 1200 rev/min)

5. Sketch the Speed - Torque characteristic for a series motor and shunt motor. Explain why the series motor is more suited to traction and winching operations.

6.10 **D.C. SERVO MOTORS MANUFACTURERS APPROACH**

Smaller servo motors are used for robotic applications, that is, the control of position and speed of a shaft. They may use field control or armature control or both.

FIELD CONTROL

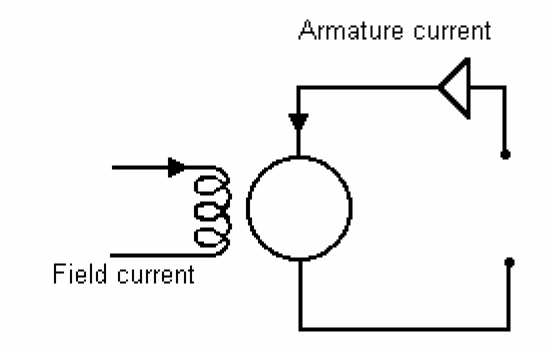


The armature current I_a is maintained constant and the field current I_f is supplied through a power amplifier and controls the torque. The torque is unaffected by the speed. The relationship between torque and current is

$$T = k\, I_f$$

Figure 22

ARMATURE CONTROL



This is quite common since smaller servo motors use permanent magnets. With the development of more powerful permanent magnets, DC servo motors are improving their power to weight ratio but are still not as good as hydraulic motors in this respect.

Figure 23

Manufacturers of such motors present the steady state characteristics based on equations 7 and 8. However some practical aspects must be brought in. First, there is a permanent loss of torque due to friction and a current is needed to overcome friction torque before any useful torque is produced. This is expressed as T_f in catalogues.

There is also a loss of torque due to damping which is directly proportional to the speed of the motor. This torque is T_d and is found by

$$\mathbf{T_d = k_d N} \quad \text{where N is in 1000 rev/min.}$$

The other important constants quoted for such motors are the Torque constant k_t and the e.m.f. constant k_e. Torque is normally quoted in N cm which is not a recommended SI unit and the shaft speeds are quoted in 1000 rev/min.

The current required to operate such a motor is given by the equation

$$\mathbf{I = (T_L + T_f + T_d)/k_t} \quad \text{where } T_L \text{ is the load torque.}$$

The useful torque from the motor is $\mathbf{T_L = k_t I - T_f - T_d}$

The voltage required at the terminals is $\mathbf{V = (N\, k_e/1000) + (I_a R_a)}$

WORKED EXAMPLE No.3

1. Using the manufacturers data sheet, determine the terminal voltage and current required to produce a torque of 75 Ncm at 2000 rev/min.

SOLUTION

From the data sheet the GR12C has the following constants.
k_t = 10.8 N cm per Amp.
k_e = 11.3 V per 1000 rev/min
k_d = 1.16 N cm per 1000 rev/min
T_f = 4.2 N cm
Armature resistance = 0.95 Ohms.
Voltage at 3000 rpm is 44.5 V
$T_d = (N/1000) \times k_d = (2000/1000) \times 1.16 = 2.32$ N cm

$$I = (T_L + T_f + T_d)/k_t = (75 + 4.2 + 2.32)/10.8 = 7.55 \text{ A}$$
$$V = (N k_e/1000) + (I_a R_a)$$
$$V = (2000 \times 11.3/1000) + (7.55 \times 0.95) = 29.8 \text{ V}$$

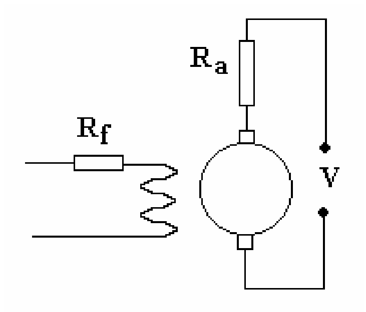
DATA TABLES FOR MOTORS

Motor Constants		GR12C	GR12CH	GR16C	GR16CH	GR19CH
Torque	K_t Ncm/Amp	10.8	17.0	23.7	37.3	24.0
EMF	K_e V/krpm	11.3	17.8	24.8	39.0	25.0
Damping	K_d Ncm/krpm	1.16	1.95	3.57	6.44	7.76
Friction Torque	T_f Ncm	4.2	4.2	7.7	7.7	9.8
Terminal Resistance @ 5A	R_m Ohm	0.95	0.95	0.95	0.95	0.65
Rotor Moment of Inertia	J kg.cm^2	1.2	1.2	5.93	5.93	12.71

SELF ASSESSMENT EXERCISE No.3

Using the manufacturers data sheet determine the voltage and current needed to run the motor GR16C at 3000 rev/min with a load torque of 40 N cm. (Answer 76.7 V)

7. STARTING LARGE D.C. MOTORS



Consider a basic D.C Motor. The terminal voltage is V. The back e.m.f on the armature is E. The armature resistance is R_a. The field resistance is R_f. The flux per pole is Φ. N is the motor speed.

Figure 24

From earlier work it was shown that $V = E + I_a R_a$ $E = K_1 N\Phi$ $T = K_2 \Phi I_f$
When the motor is started, the speed is zero so there is no back e.m.f. It follows that $V = I_a R_a$
The starting current without protection would be V/R_a and this would be very large. In addition to this, there will be a load with inertia connected to the motor and a large current is needed to provide the torque.

WORKED EXAMPLE No.4
A motor with a separate field coil has a terminal voltage V = 400 V and an armature resistance of 0.2Ω. Calculate the starting current in the armature.

SOLUTION $I_a = V/ R_a = 400/0.2 = 2000$ Amps.

In order to limit the current, it is normal to insert a variable resistance in series with the armature which is gradually reduced as the motor speeds up and then latched in place in the zero resistance position. In the event of an interruption to the power, the starting resistance is unlatched and springs back to the starting position. We should consider how the starting resistance is used with different motor field configurations. The three types or configurations are shown below.

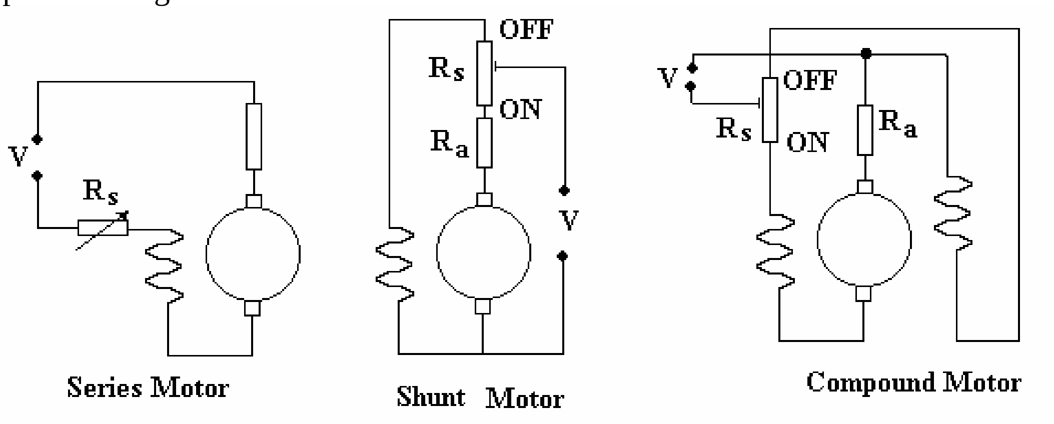


Figure 25

SERIES MOTOR
In the case of a series wound motor, the starting resistance is placed in series as shown.

SHUNT MOTOR
In the case of a shunt wound motor, the starting resistance is placed as shown so that the field is initially connected to the supply and the armature is in series with it. As the motor speeds up the field resistance is gradually increased and the resistance in series with the armature is reduced.

COMPOUND MOTOR
Compound motor has a starting resistance as shown.

8. THE EFFECT OF INERTIA AND INDUCTANCE

Most of the work covered so far has been concerned with the steady state analysis of motors. When sudden changes are made to the speed or torque, it takes time for the system to respond because of the time dependant effects such as inertia, damping and inductance. A motor may have damping torque which is directly proportional to speed. This was given previously as:

$$T_d = K_d \times N/1000 \quad \text{where N is rev/min and T is in Ncm.}$$

If we use S.I. units the damping torque would be given by:

$$T_d = K_d\,\omega \quad \text{where } \omega \text{ is rad/s and T is Nm}$$

ω is the rate of change of angle per second and may be expressed in calculus form as $d\theta/dt$. Hence:

$$T_d = K_d\, d\theta/dt.$$

If the motor is accelerated, torque is needed to overcome the inertia T_i and this is directly proportional to the angular acceleration. $T_i = I\alpha$

α is in rad/s^2 and I is the moment of inertia in kg m^2. (Many manufacturers use the symbol J for moment of inertia)

The acceleration is the second derivative of angle with respect to time so we may write $T_i = I\, d^2\theta/dt^2$

When a motor is producing acceleration the total torque acting on it is

$$T = T_L + T_f + K_d\, d\theta/dt + I\, d^2\theta/dt^2$$

This results in a mechanical time constant τ_m which governs how quickly a motor will accelerate. This is defined by manufacturers as the time taken to accelerate the motor up to 63% of the required speed with no load on it. This will be analysed and defined in detail in another tutorial. Now consider that the terminal voltage of a servo motor was defined earlier as $V = E_a + I_aR_a$

If the current is changing, the inductance of the armature winding also produces a voltage (back emf) given by L di/dt where L is the inductance in Henries and i the transient current.

The total terminal voltage is then $V = L\, di/dt + E_a + I_aR_a$

This gives rise to an electrical time constant defined as $\tau_e = L/R_a$

This will be explained in another tutorial.

If the motor uses field control, the electrical time constant is based on the field winding inductance and resistance.

WORKED EXAMPLE No.5

A d.c. servo motor must accelerate from rest to 30 rad/s in 3 seconds. The rotating mass has a moment of inertia of 5 kg m^2. The load torque is 20 N m and the friction torque is 1.2 Nm. The damping coefficient is 0.05 Nm s/radian. The torque constant is 120 Nm per ampere.

Determine the required current just before the acceleration ends.

SOLUTION

$T_L = 20$ Nm

$T_f = 1.2$ Nm

$\omega = 30$ rad/s $\qquad T_d = K_d\,\omega = 0.05 \times 30 = 1.5$ Nm

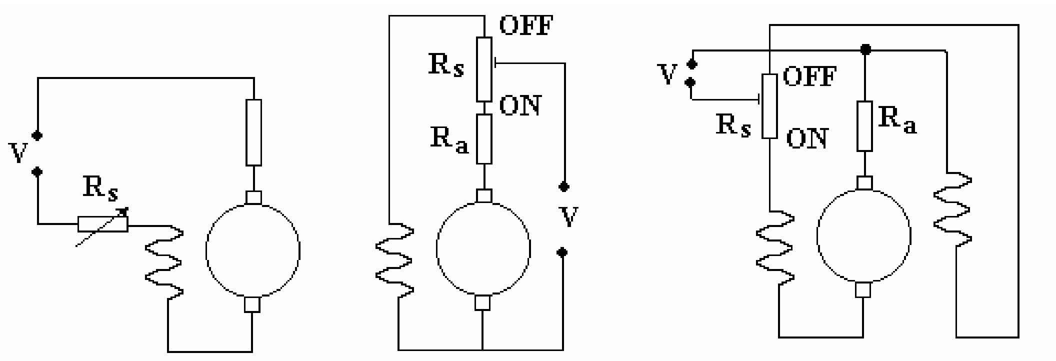
$\alpha = (30 - 0)/3 = 10$ rad/s^2 $\qquad T_i = I\alpha = 5 \times 10 = 50$ Nm

$T = T_L + T_f + T_d + T_i = 20 + 1.2 + 1.5 + 50 = 72.7$ Nm

$I = 72.7/120 = 0.606$ Amperes

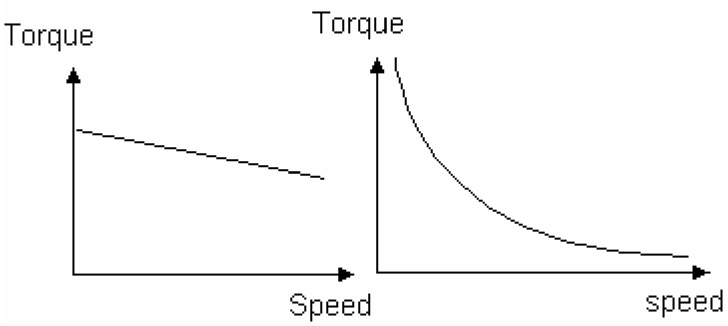
SELF ASSESSMENT EXERCISE No.4

1. Identify which of the diagrams shows a series, shunt and compound wound motor.



A B C

2. Identify which torque - speed graph represents series and shunt wound motors.



3. A DC servo motor has the following constants.

k_e = 7.1 V per 1000 rev/min
k_t = 6.7 Ncm /A
k_d = 0.78 Ncm per 1000 rev/min
T_f = 3.2 Ncm
R_a = 0.85 Ohm

Calculate the current, terminal voltage and electric power when the motor speed is 3000 rev/min and the load torque is 45 Ncm. (27.71 V, 7.543 A and 209 W)

4. A 500V shunt wound d.c. motor has an armature resistance of 0.5Ω and a field coil resistance of 250Ω. Calculate the total current taken from the source at start up. What value resistance must be placed in series with the armature to reduce the starting current to 50A? (9.917 Ω)

5. A d.c. servo motor must accelerate from rest to 15 rad/s in 2 seconds. The rotating mass has a moment of inertia of 2 kg m^2. The load torque is 12 Nm and the friction torque is 1.5 Nm. The damping coefficient is 0.08 Nm s/radian. The torque constant is 90 Nm per ampere.

Determine the required current just before acceleration ends. (0.33 A)