UNIVERSITY OF TECHNOLOGY, SYDNEY
FACULTY OF ENGINEERING

48531 Electromechanical Systems

Stepping Motors and Their Power Electronic Drives

Topics to cover:

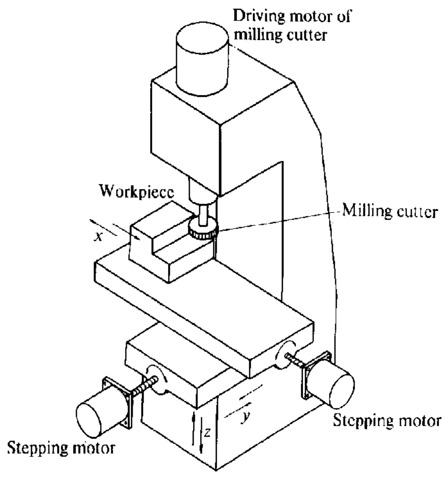
1. Introduction | *2. Types and Principles*

3. Drive Circuits | *4. Characteristics*

5. Low Speed Operation | *6. High Speed Operation*

Introduction

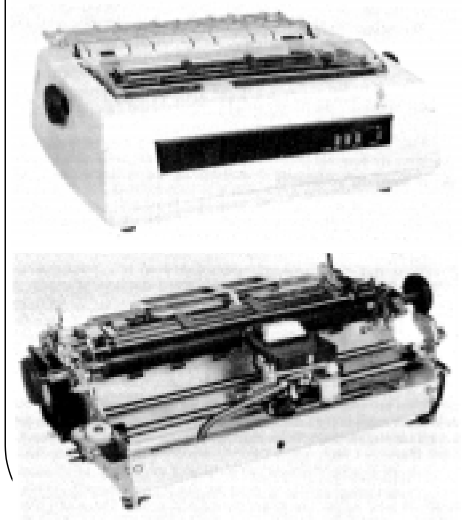
Stepping motors have been developed in response to the demand for a device capable of ***producing a definite angular displacement*** in a driven shaft and holding its position against a torque applied to the driven shaft. Stepping motors are commonly used in applications, such as numerically controlled machine tools, electronic instruments, and computer peripherals.

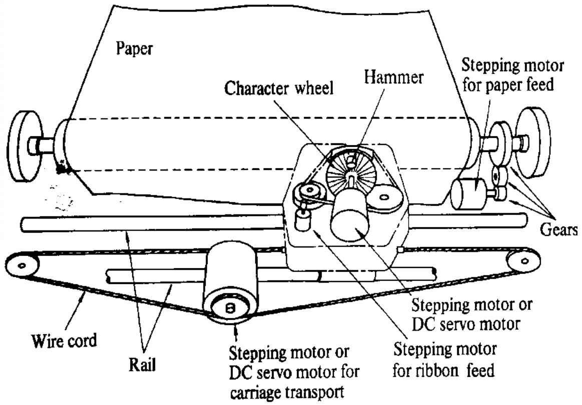


A numerically controlled milling machine

Introduction

- *Stepping Motor Applications: Serial Printer*

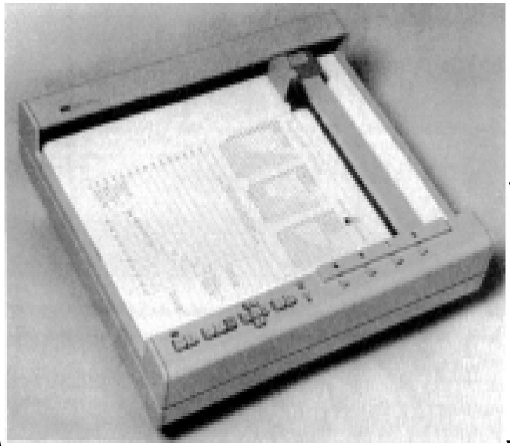


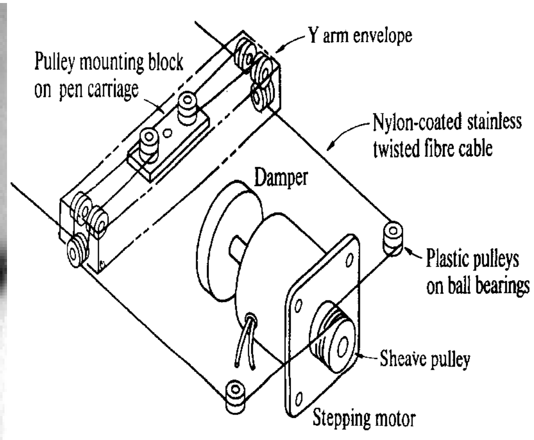


External view, internal mechanism, and fundamental construction of character-impact type serial printer

Introduction

- *Stepping Motor Applications: X-Y Plotter*

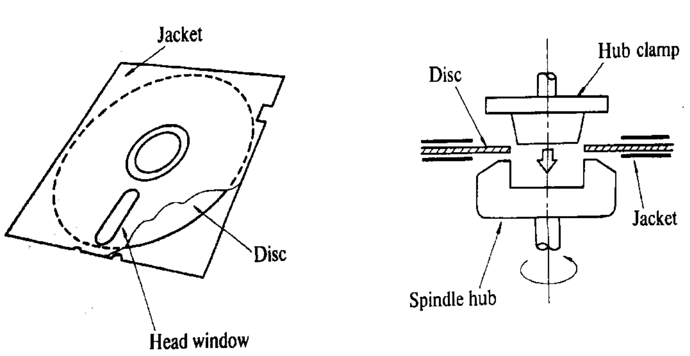


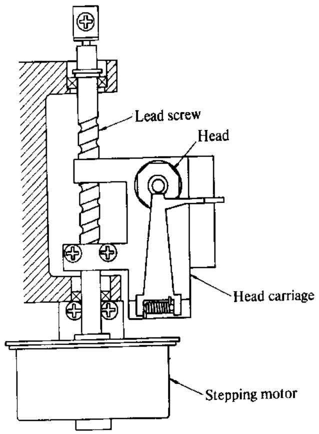


An X-Y plotter and the pen drive system

Introduction

- Stepping Motor Applications: Disk Drive

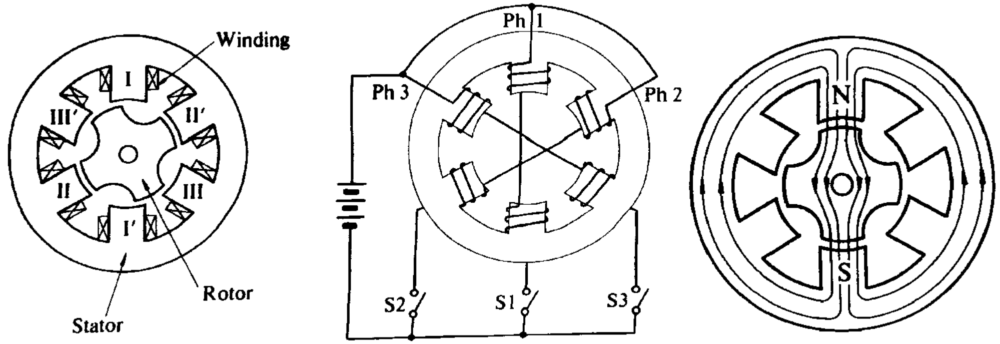




Floppy disc structure and mounting mechanism and driving mechanism of the read/write head

Types and Principles

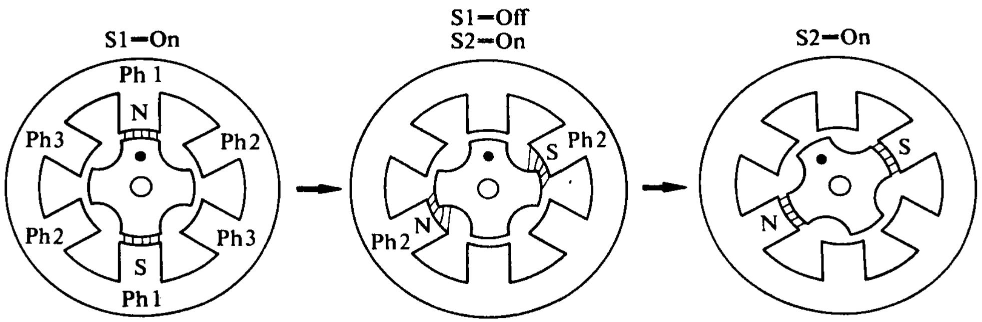
- Variable Reluctance Stepping Motor: Single Stack



Cross sectional model of a three phase VR stepping motor, winding arrangement, and equilibrium position with phase 1 excited

Types and Principles

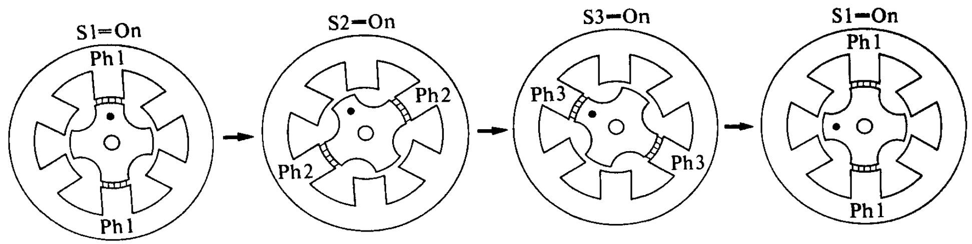
- Variable Reluctance Stepping Motor: Single Stack



How a step motion proceeds when excitation is switched from Ph1 to Ph2

Types and Principles

- Variable Reluctance Stepping Motor: Single Stack

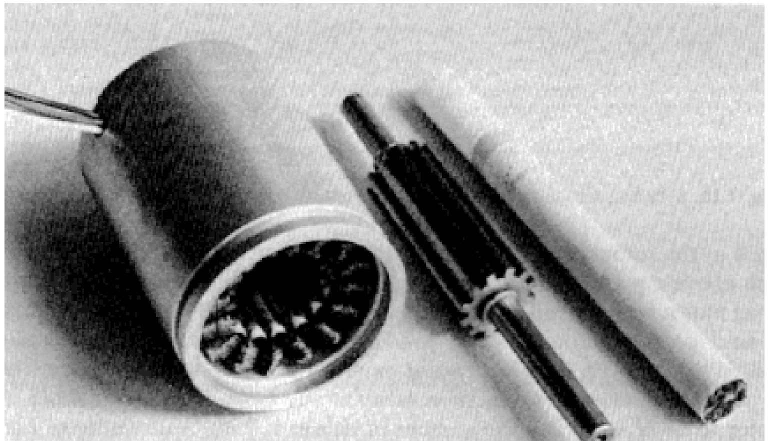


Step motions as switching sequence proceeds in a three phase VR motor

$$\boxed{S = \frac{360}{\theta_s} = mN_r}$$

Types and Principles

- Variable Reluctance Stepping Motor: Single Stack

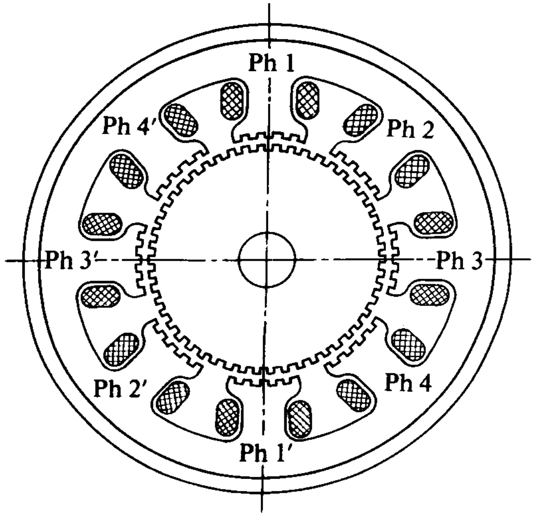


(16 stator teeth and 12 rotor teeth)

Stator and rotor of a four phase VR motor of 7.5^o step angle

Types and Principles

- Variable Reluctance Stepping Motor: Single Stack



To reduce the step angle, the number of the rotor teeth can be increased.

The diagram on the right hand side shows the cross sectional view of a typical four phase VR stepping motor with 50 rotor teeth. The step number is 200 and step angle equals 1.8^o

Types and Principles

- Variable Reluctance Stepping Motor: Single Stack

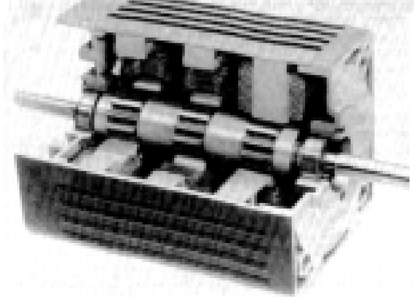
The step angle can be further reduced by the so called 'half-step excitation mode', which is a combination of the single phase and two phase excitation. The switching sequence for the 3 phase 4 rotor teeth stepping motor is illustrated in the table below. Obviously, the step angle is halved.

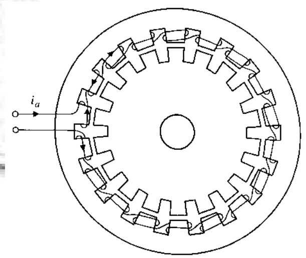
Step	1	2	3	4	5	6
S1	1	1	0	0	0	1
S2	0	1	1	1	0	0
S3	0	0	0	1	1	1

$$\boxed{S = \frac{360}{\theta_s} = 2mN_r}$$

Types and Principles

- Variable Reluctance Stepping Motor: Multi-Stack





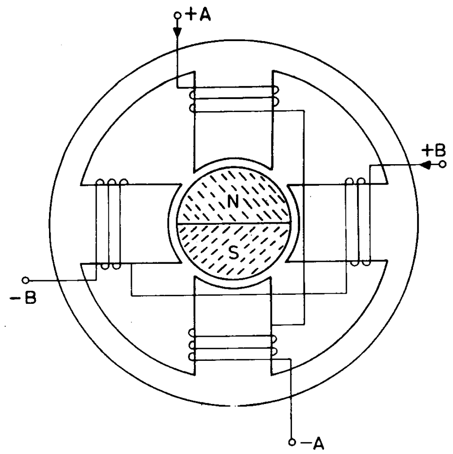
$$\boxed{S = \frac{360}{\theta_s} = mN_r}$$

In each stack, the rotor and stator have equal numbers of teeth. Adjacent stator teeth have equal and opposite magnetomotive forces produced by windings carrying the phase current. On the same shaft, normally, there are *m* similar stacks. Each of these has either its rotor or its stator displaced sequentially from its neighbour by a tooth pitch divided by *m*, and each is excited by a phase current.

Types and Principles

- Permanent Magnet Stepping Motor

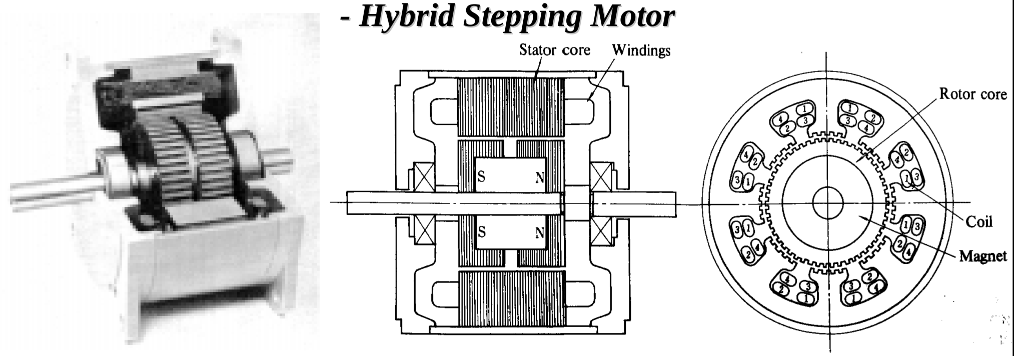
The ***current polarity*** is important in the permanent magnet motor. An advantage of this type of machine is that ***the rotor tends to remain in its last position when phase current is removed***. It is difficult to manufacture a small permanent magnet motor with a great number of poles and consequently stepping motors of this type are restricted to step lengths in the range 30°-90°.



$$\boxed{S = \frac{360}{\theta_s} = mN_r}$$

Types and Principles

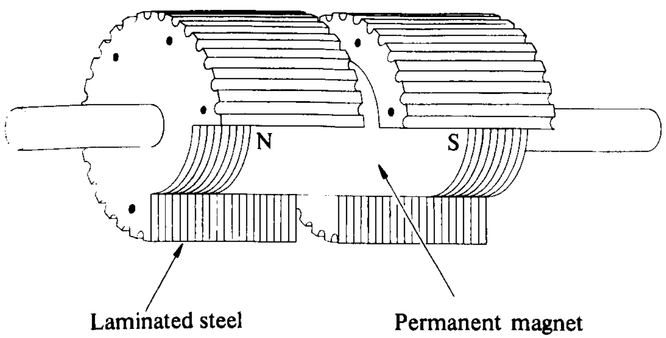
- Hybrid Stepping Motor



The hybrid stepping motor is operated under the combined principles of the permanent magnet and variable reluctance motors. In the four phase hybrid motor above, the stator core structure is very close to that of a single stack VR motor, but the two coils at a pole are wound in the bifilar scheme such that they produce different magnetic polarities on excitation.

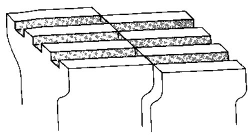
Types and Principles

- Hybrid Stepping Motor (Cont.)



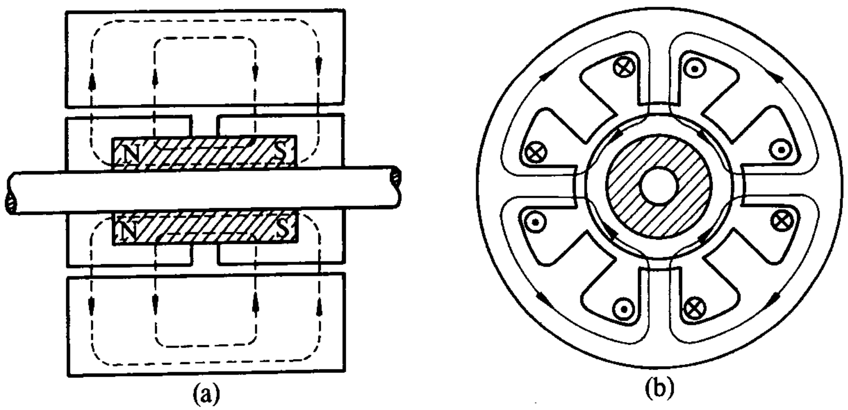
A cylindrical magnet lies in the rotor core, and it is magnetized lengthwise to produce a unipolar field. Each pole of the magnet is covered with uniformly toothed soft steel.

The teeth on the two sections are misaligned with respect to each other by half tooth pitch. In some motors, the rotor teeth are aligned with each other, but the stator core has a misalignment.



Types and Principles

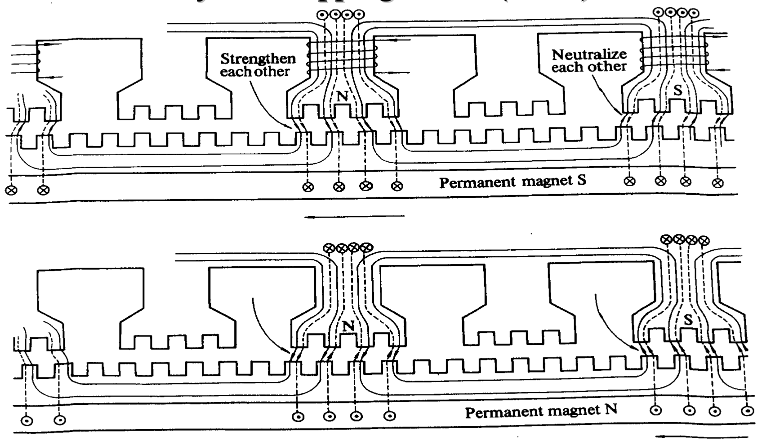
- Hybrid Stepping Motor (Cont.)



The magnetic field in a hybrid stepping motor, (a) unipolar flux generated by the magnet, and (b) heteropolar flux by the stator coils

Types and Principles

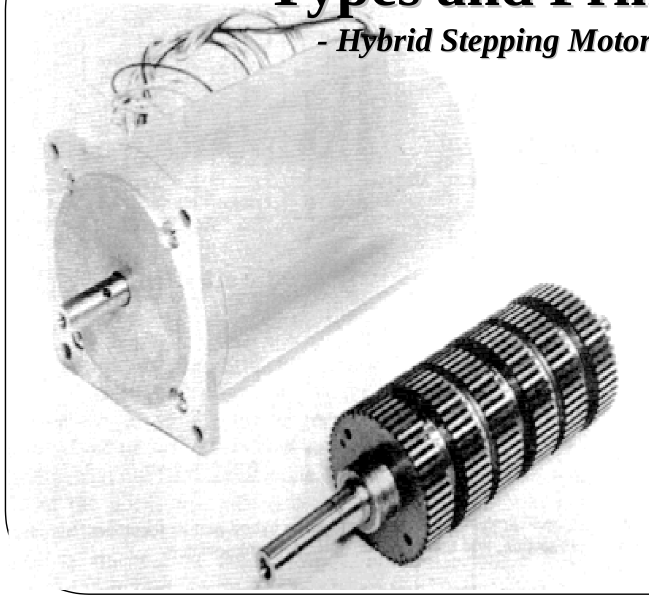
- Hybrid Stepping Motor (Cont.)



Split and unrolled model of a four phase hybrid stepping motor; the upper and the lower being the south and north pole cross sections, respectively

Types and Principles

- Hybrid Stepping Motor (Cont.)

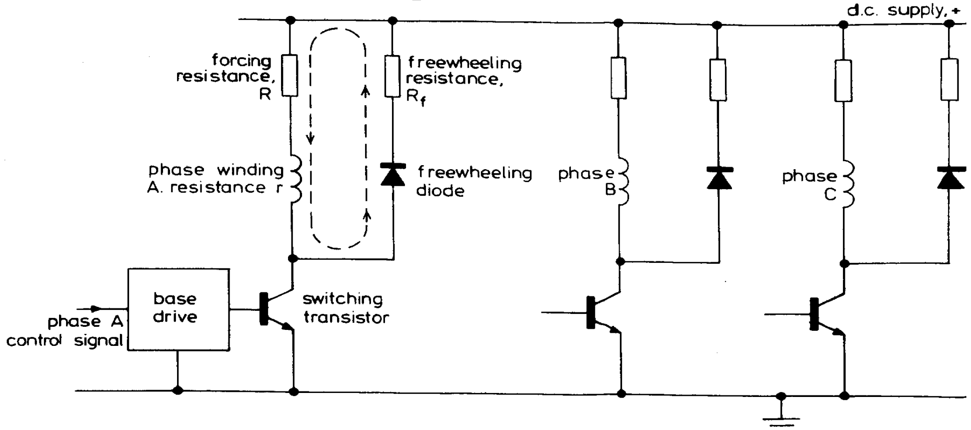


The most popular hybrid motor is the four phase 200 step motor, the step angle being 1.8°.

In order to raise the torque, multi-stack hybrid motors are employed.

Power Electronic Drives

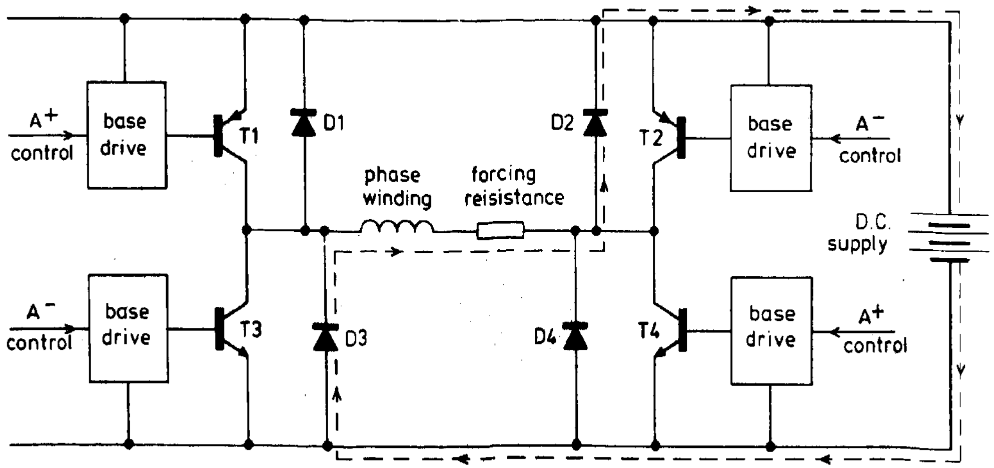
- Unipolar Drive Circuit



A simple unipolar drive circuit suitable for use with a three phase variable reluctance stepping motor

Power Electronic Drives

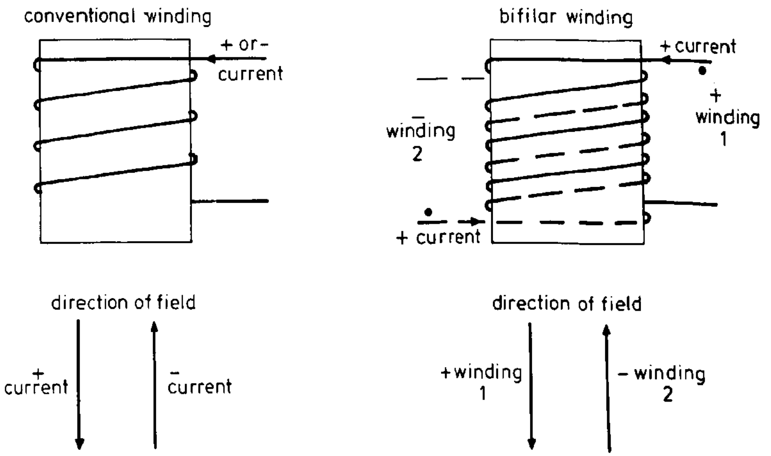
- Bipolar Drive Circuit



One phase of a transistor bridge bipolar drive circuit

Power Electronic Drives

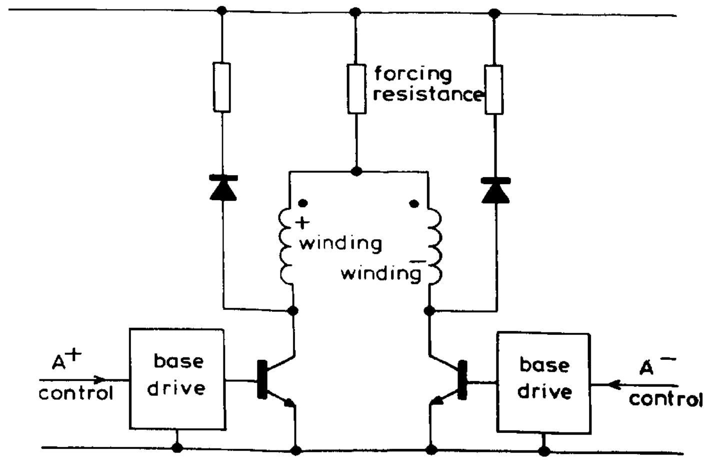
- Bifilar Windings



Comparison of conventional and bifilar windings

Power Electronic Drives

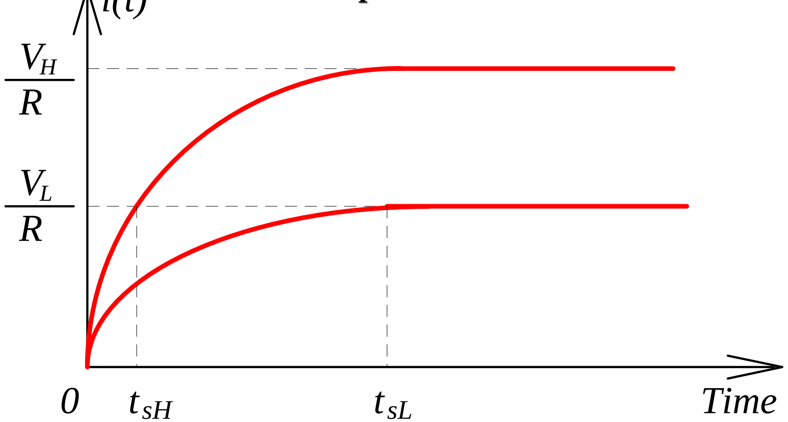
- Bifilar Windings plus Unipolar Drive Circuit



Unipolar drive circuit for one phase of a bifilar-wound motor

Power Electronic Drives

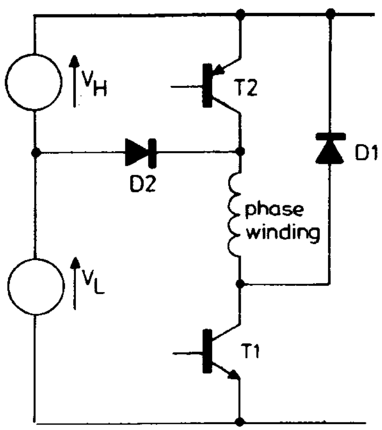
- Bilevel Unipolar Drive Circuit

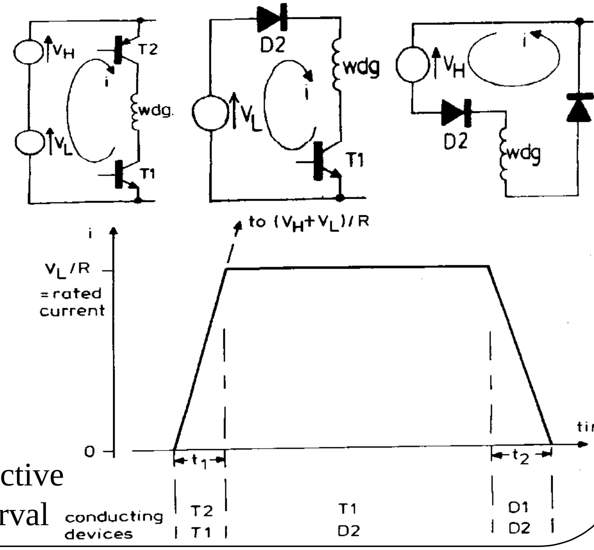


Principle of increasing the step response speed by using bilevel power supply

Power Electronic Drives

- Bilevel Unipolar Drive Circuit

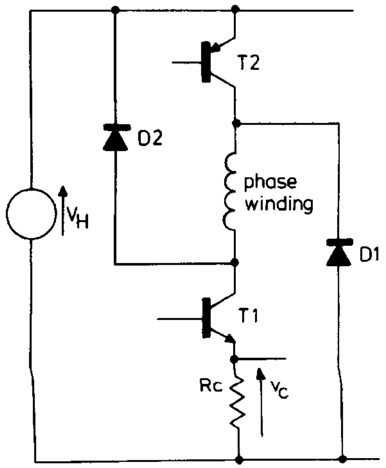


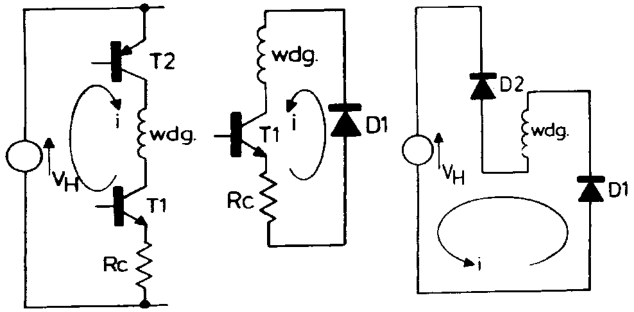


The bilevel drive and the effective circuits during excitation interval

Power Electronic Drives

- Chopper Unipolar Drive Circuit

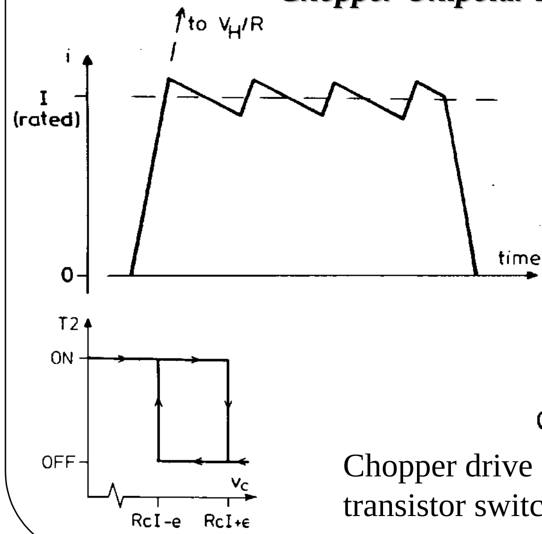


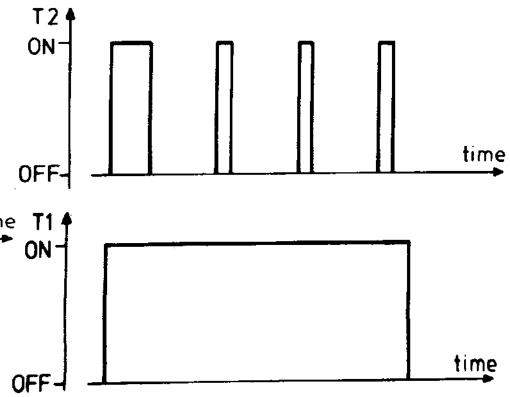


Chopper drive circuit and current paths during excitation interval

Power Electronic Drives

- Chopper Unipolar Drive Circuit (Cont.)





Chopper drive current waveform and transistor switching times

Static Characteristics

- Static Torque/Rotor Position characteristic

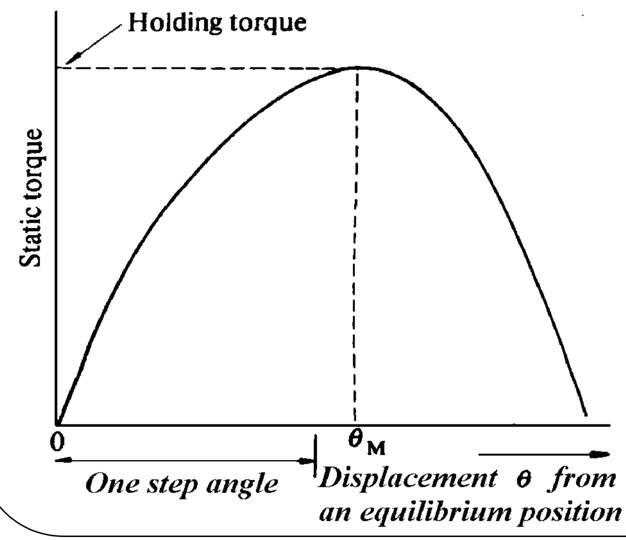
The characteristics relating to stationary motors are called static characteristics.

<u>Static Torque/Rotor Position Characteristic</u>

The stepping motor is first kept stationary at a rest (equilibrium) position by supplying a current in a specified mode of excitation, say, single-phase or two phase excitation. If an external torque is applied to the shaft, an angular displacement will occur. The relation between the external torque and the displacement is conventionally called the T/θ characteristic curve, and the maximum of static torque is termed the 'holding torque', which occurs at $\theta=\theta_M$. At displacements larger than θ_M, the static torque does not act in a direction towards the original equilibrium position, but in the opposing direction towards the next equilibrium position.

Static Characteristics

- Static Torque/Rotor Position characteristic (Cont.)

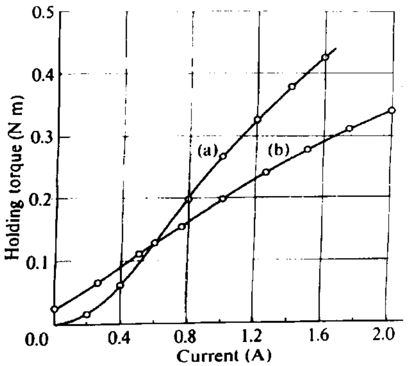


The ***holding torque*** is rigorously defined as '***the maximum static torque that can be applied to the shaft of an excited motor without causing continuous motion***'. The angle at which the holding torque is produced is not always separated from the equilibrium point by one step angle.

Static Characteristics

- Static Torque/Stator Current characteristic

The holding torque increases with current, and this relation is conventionally referred to as ***T/I*** characteristics. The diagram below compares the ***T/I*** character-istics of a typical hybrid motor with those of a variable-reluctance motor, the step angle of both being 1.8°.

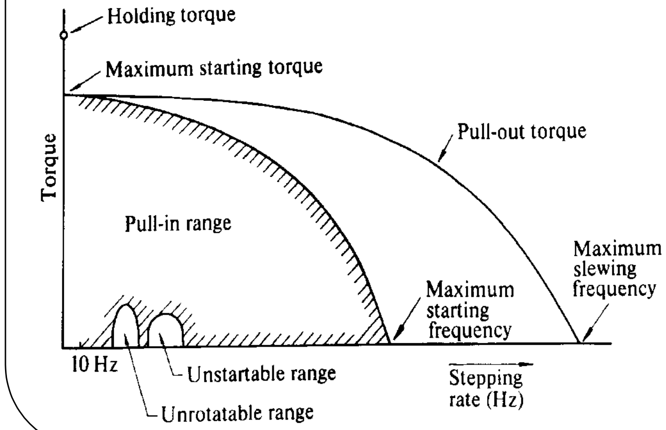


Curves (a) and (b) are *T/I* curves of VR and hybrid stepping motors, respectively. The maximum static torque appearing in the hybrid motor with no current is the detent torque, which is defined as the maximum static torque that can be applied to the shaft of an unexcited motor without causing continuous rotation.

Dynamic Characteristics

- Pull-in torque characteristic

The characteristics relating to motors which are in motion or about to start are called dynamic characteristics.



The ***pull-in torque charateristic*** is alternatively called the ***starting characteristic*** and refer to the range of frictional load torque at which the motor can start and stop without losing steps for various frequencies in a pulse train.

Dynamic Characteristics

- Pull-out torque characteristic

The pull-out torque charateristic is alternatively called the ***slewing characteristic***.

Testing Method:

After the test motor is started by a specified driver in the specified excitation mode in the self-starting range, the pulse frequency is gradually increased; the motor will eventually run out of synchronism. The relation between the frictional load torque and the maximum pulse frequency with which the motor can synchronize is called the pull-out characteristic. The pull-out curve is greatly affected by the driver circuit, coupling, measuring instruments, and other conditions.

Dynamic Characteristics

- Other Dynamic Characteristics

The Maximum Starting Frequency

This is defined as the maximum control frequency at which the unloaded motor can start and stop without losing steps.

Maximum Pull-out Rate

This is defined as the maximum frequency (stepping rate) at which the unloaded motor can run without losing steps, and is alternatively called the 'maximum slewing frequency'.

Maximum Starting Torque

This is alternatively called 'maximum pull-in torque' and is defined as the maximum frictional load torque with which the motor can start and synchronize with the pulse train of a frequency as low as 10Hz.

Low Speed Operation

- *Mathematical Model*

At low speeds, each individual step is discernable and the behaviour is a series of step input transients. The motor must be modelled by a set of differential equations, which are in general nonlinear. Approximations may be made to linearize the equations for analytical solutions. Otherwise the solution must be “marched out” in time using a computer numerical method, as explained in the “Principles of Electromechanical Energy Conversion”. For a VR stepping motor with one phase winding excited, the state equation model is

$$\frac{di}{dt} = -\frac{1}{L}\left[R + \frac{dL(\theta)}{d\theta}\omega_r\right]i + \frac{1}{L}v$$

$$\frac{d\omega_r}{dt} = \frac{1}{J}T - \frac{1}{J}T_{load}$$

and $$\frac{d\theta}{dt} = \omega_r$$

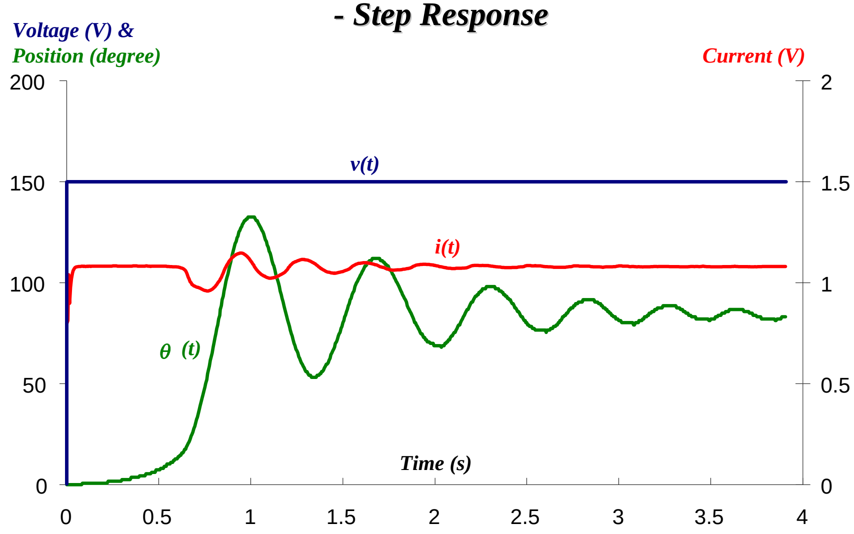
The initial conditions are

$$i\big|_{t=0} = i_0 \quad \omega_r\big|_{t=0} = \omega_{r0}$$

and $$\theta\big|_{t=0} = \theta_0$$

Low Speed Operation

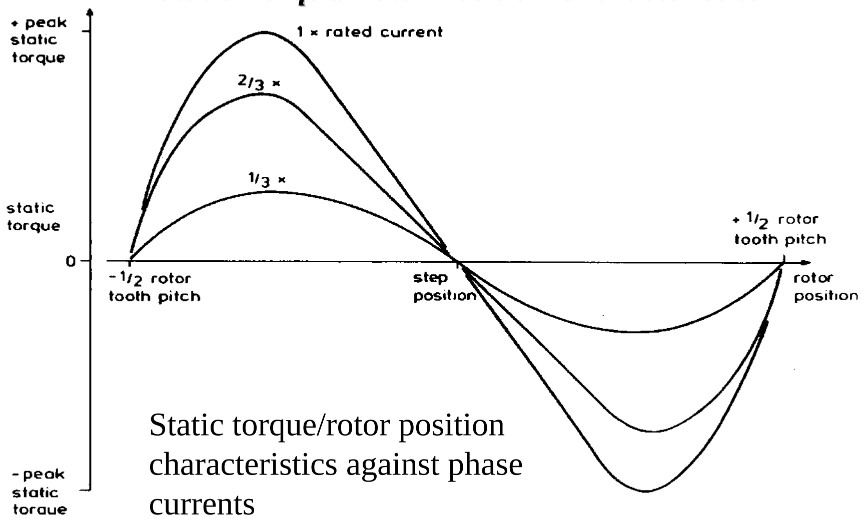
- *Step Response*



Step response of a VR stepping motor

Low Speed Operation

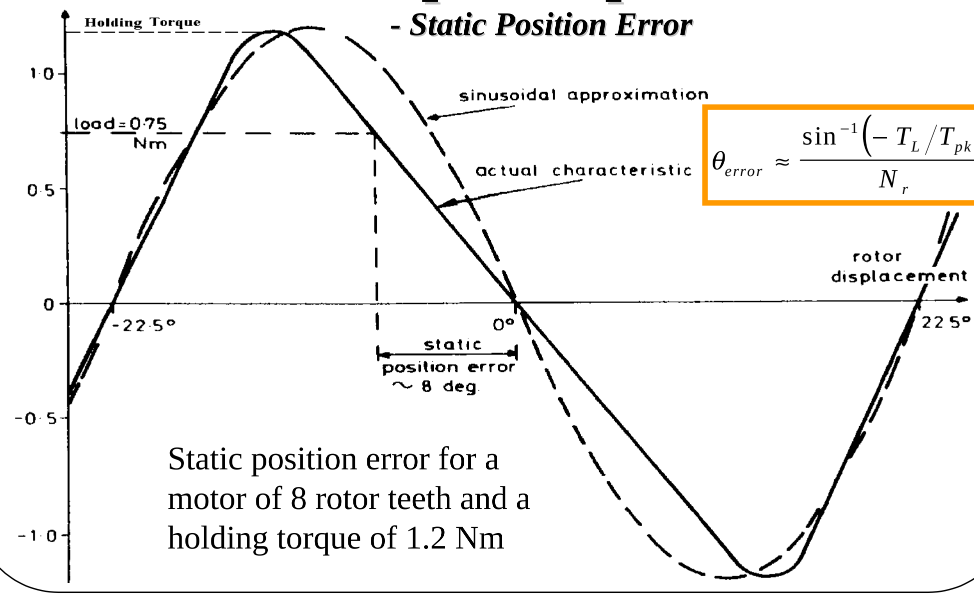
- *Static Torque/Rotor Position Characteristics*



Static torque/rotor position characteristics against phase currents

Low Speed Operation

- *Static Position Error*

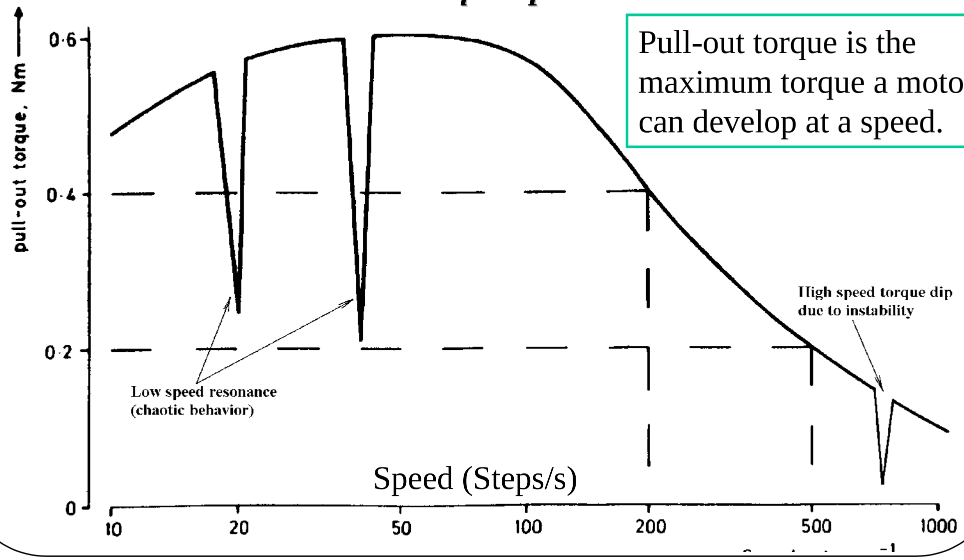


$$\theta_{error} \approx \frac{\sin^{-1}\left(-T_L/T_{pk}\right)}{N_r}$$

Static position error for a motor of 8 rotor teeth and a holding torque of 1.2 Nm

Low Speed Operation

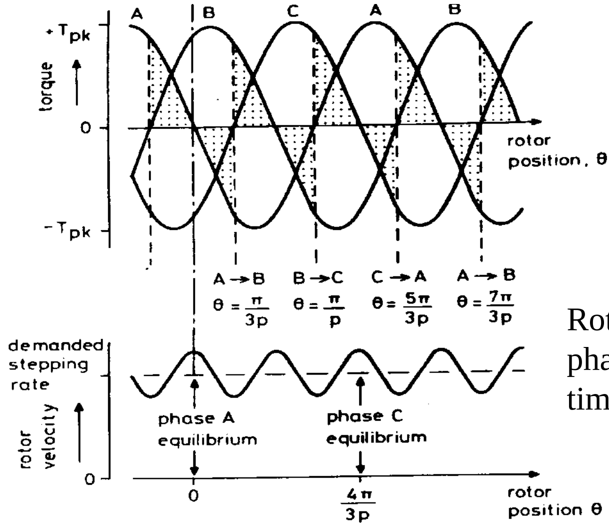
- Pull-out Torque/Speed Characteristic



Pull-out torque is the maximum torque a motor can develop at a speed.

Low Speed Operation

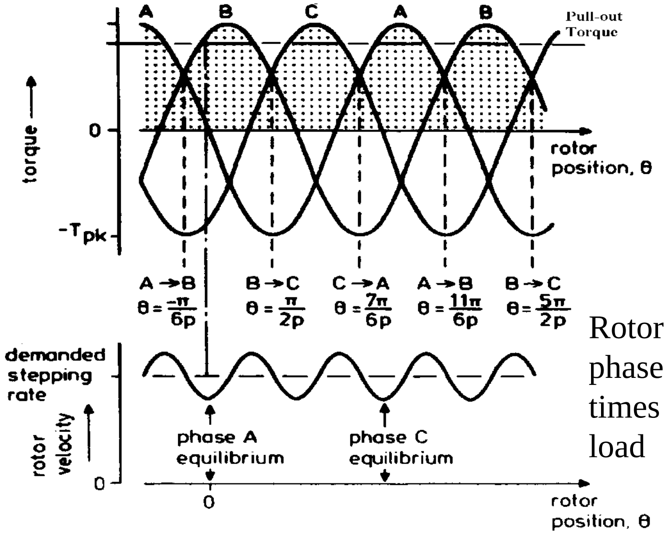
- Rotor position at phase switching times



Rotor position at phase switching times for no load

Low Speed Operation

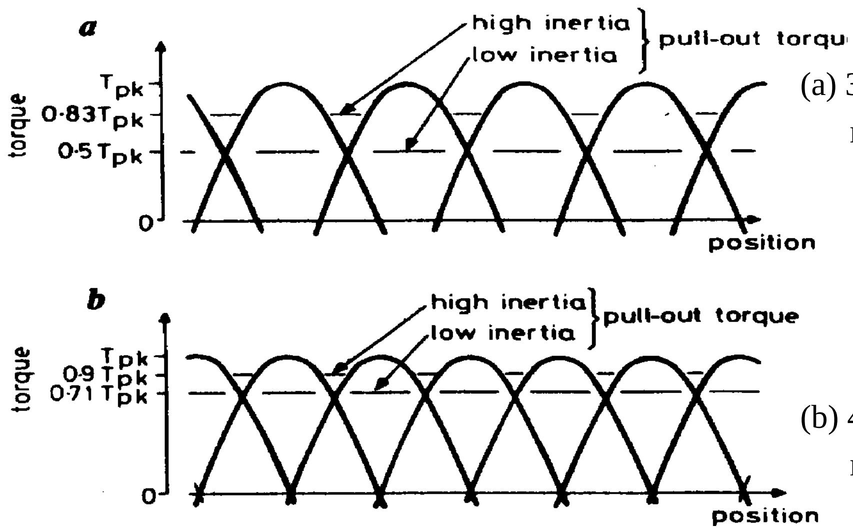
- Rotor position at phase switching times (Cont.)



Rotor position at phase switching times for pull-out load

Low Speed Operation

- Rotor position at phase switching times (Cont.)

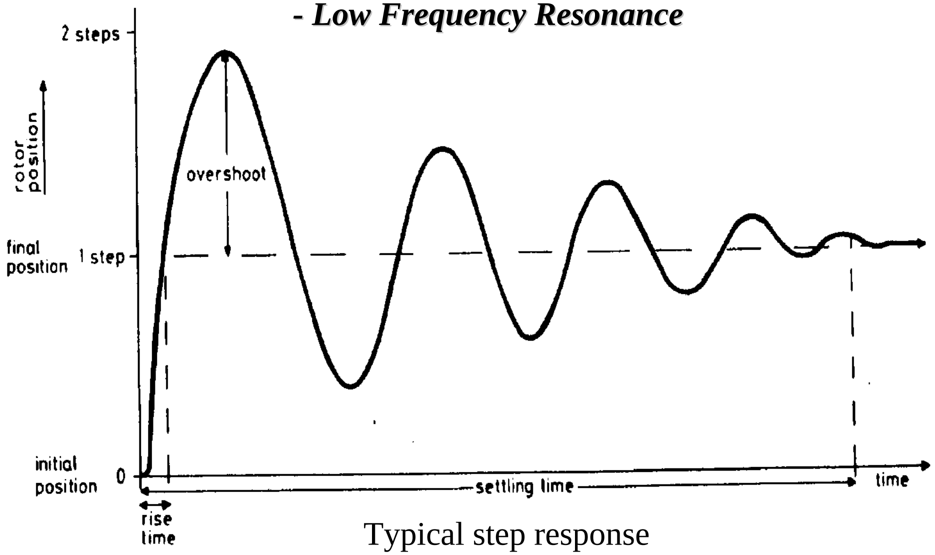


(a) 3 phase motor

(b) 4 phase motor

Low Speed Operation

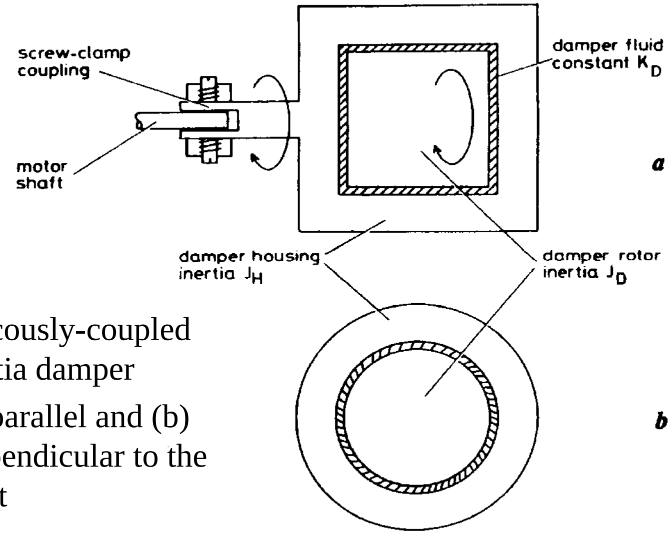
- Low Frequency Resonance



Typical step response

Low Speed Operation

- Low Frequency Resonance (Cont.)

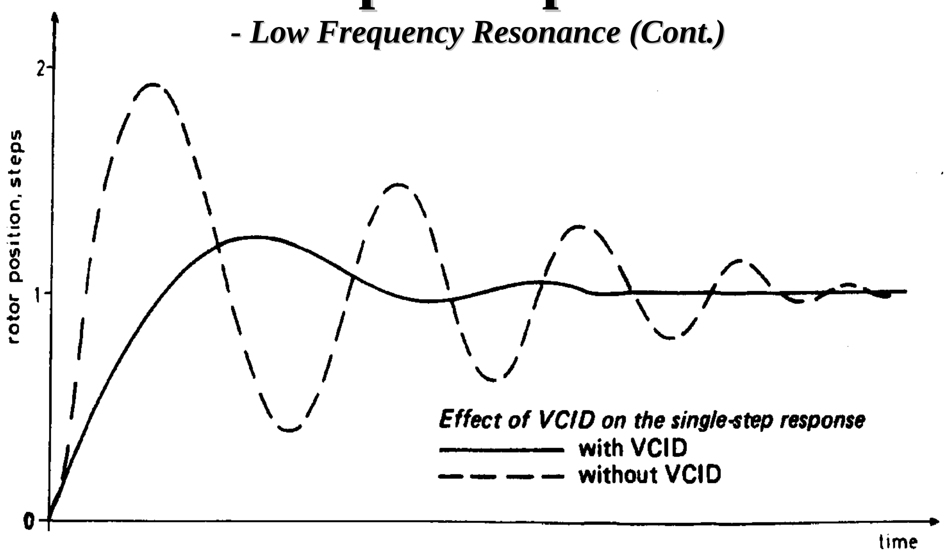


Viscously-coupled inertia damper

(a) parallel and (b) perpendicular to the shaft

Low Speed Operation

- Low Frequency Resonance (Cont.)



Effect of viscously-coupled inertia damper

High Speed Operation

- Mathematical Model

At high speeds, the steps merge into one another, and alternative methods may be used to set up and/or solve the differential equations:

(1) *Step ripple present*

The equations must be "marched-out" in time as before, or the equations can be linearized for small oscilations.

(2) *Speed ripple assumed zero*

It may be possible to use time-domain methods such as Fourier analysis and/or phasor analysis.

(3) *Speed ripple assumed zero and current assumed sinusoidal*

A.C. phasor analysis can be used, (Same model as that for synchronous motors).

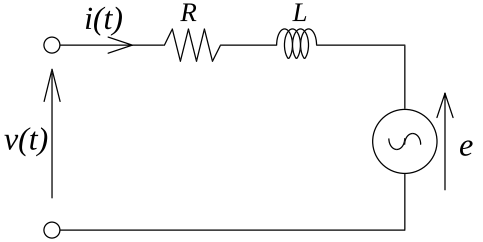
High Speed Operation

- Equivalent Circuit in Time Domain

The circuit equation for one phase excitation can be written as

$$v = Ri + L\frac{di}{dt} + \frac{dL(\theta)}{d\theta}\omega_r i + \frac{d\lambda_m}{dt}$$

where L is the stator winding inductance, λ_m the stator winding flux linkage due to the permanent magnet. The corresponding equivalent circuit is



where

$$e = \frac{dL(\theta)}{d\theta}\omega_r i + \frac{d\lambda_m}{dt}$$

High Speed Operation

- Phasor Expression of VR Stepping Motor

For a VR motor, $\lambda_m = 0$ and $L(\theta) = L_o + L_1 \sin N_r\theta$

Since unipolar drive is employed, we may express the voltage and current in the stator phase winding as

$$v(t) = V_o + V_1 \cos\omega t \quad \text{and} \quad i(t) = I_o + I_1 \cos(\omega t - \delta - \alpha)$$

Neglecting the high frequency terms, we obtain the voltage and current relations as $V_o = RI_o$

and $V_1 \cos\omega t = RI_1 \cos(\omega t - \delta - \alpha)$

$$- \omega L_o I_1 \sin(\omega t - \delta - \alpha) + \omega L_1 I_o \cos(\omega t - \delta)$$

In phasor expression, the above voltage-current relationship becomes

$$\boxed{V = RI + j\omega L_o I + E} \quad \text{where} \quad \boxed{E = \omega L_1 I_o \angle -\delta}$$

High Speed Operation

- Phasor Expression of PM and Hybrid Stepping Motors

For PM and hybrid motors, L can be considered as independent of the rotor position. The fundamental component of the voltage and current can be expressed as

$$v(t) = V \cos\omega t \quad \text{and} \quad i(t) = I\cos(\omega t - \delta - \alpha)$$

Assume the flux linkage of the stator winding due to the permanent magnet is $\lambda_m = \hat{\lambda}_m \sin(\omega t - \delta)$

Therefore, $V\cos\omega t = RI\cos(\omega t - \delta - \alpha)$

$$- \omega LI \sin(\omega t - \delta - \alpha) + \omega\lambda_m \cos(\omega t - \delta)$$

In phasor expression, the above voltage-current relationship becomes

$$\boxed{V = RI + j\omega LI + E} \quad \text{where} \quad \boxed{E = \omega\hat{\lambda}_m \angle -\delta}$$

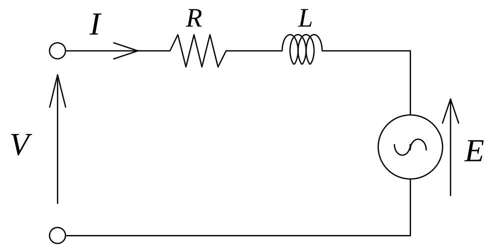
High Speed Operation

- Equivalent Circuit in Frequency Domain

A common phasor expression for all stepping motors is

$$\boxed{V = RI + j\omega LI + E}$$

and the corresponding steady state equivalent circuit is



where

$$\boxed{E = \omega L_1 I_o \angle -\delta}$$

for a VR motor, and

$$\boxed{E = \omega\hat{\lambda}_m \angle -\delta}$$

for a PM or hybrid motor.

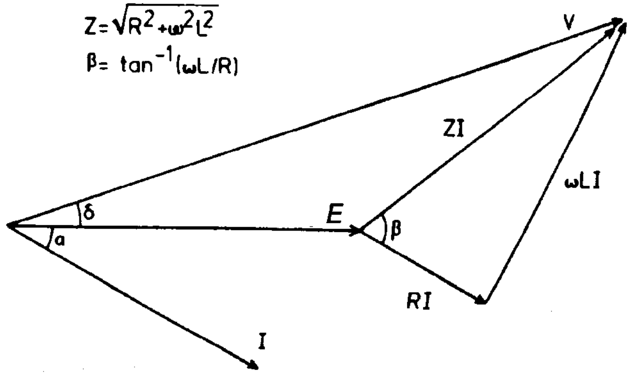
High Speed Operation

- Phasor Diagram

The corresponding phasor diagram for the steady state equivalent circuit and the phasor voltage equation

$$\boxed{V = RI + j\omega LI + E}$$

can be drawn as



High Speed Operation

- Pull-out Torque

From the phasor diagram, it can be derived that the electromagnetic torque

$$\boxed{T = \frac{pmEI\cos(\beta-\delta)}{\omega\sqrt{R^2+\omega^2L^2}} - \frac{pmE^2R}{\omega\left(R^2+\omega^2L^2\right)}}$$

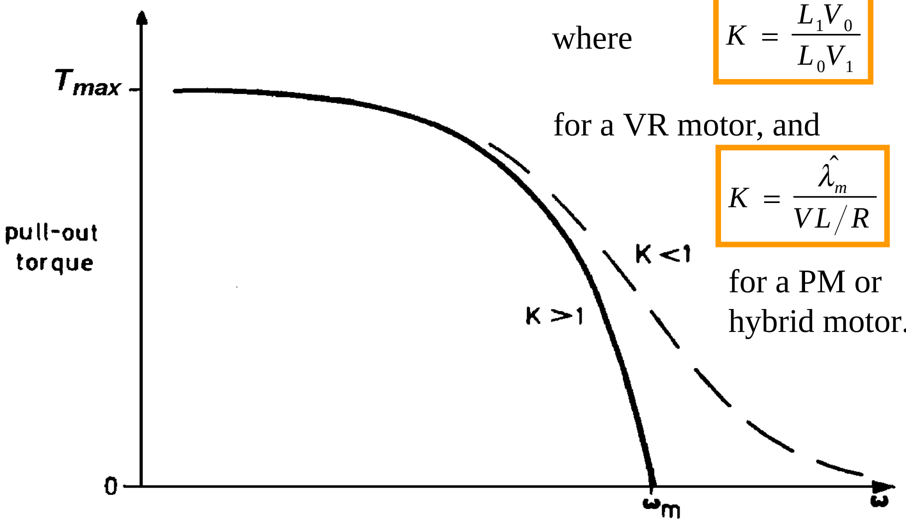
where m is the number of phases, and $p = N_r/2$ the pole pairs of the motor.

The pull-out torque is the max. torque for a certain speed, and can be determined by letting δ = β. Therefore,

$$\boxed{T_{\max} = \frac{pmEI}{\omega\sqrt{R^2+\omega^2L^2}} - \frac{pmE^2R}{\omega\left(R^2+\omega^2L^2\right)}}$$

High Speed Operation

- Predicted Pull-out Torque/Speed Characteristics



where $\boxed{K = \frac{L_1V_0}{L_0V_1}}$

for a VR motor, and

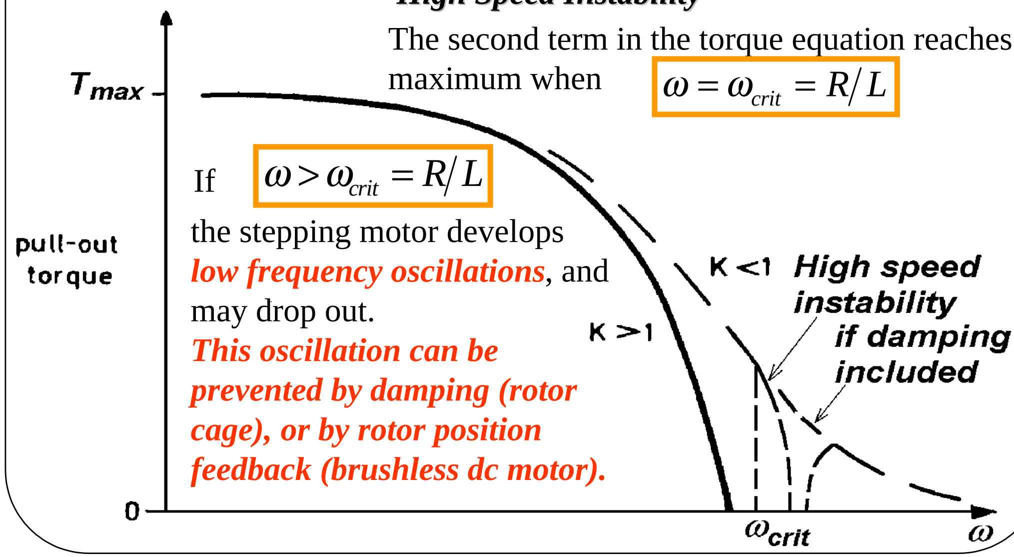
$$\boxed{K = \frac{\hat{\lambda}_m}{VL/R}}$$

for a PM or hybrid motor.

High Speed Operation

- High Speed Instability

The second term in the torque equation reaches maximum when $\boxed{\omega = \omega_{crit} = R/L}$



If $\boxed{\omega > \omega_{crit} = R/L}$

the stepping motor develops *low frequency oscillations*, and may drop out.

This oscillation can be prevented by damping (rotor cage), or by rotor position feedback (brushless dc motor).