Equal Pitch and Unequal Pitch:

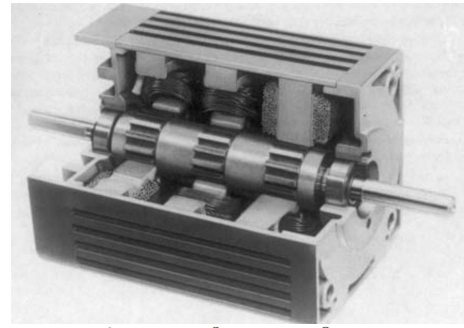
Equal-Pitch Multiple-Stack Stepper:

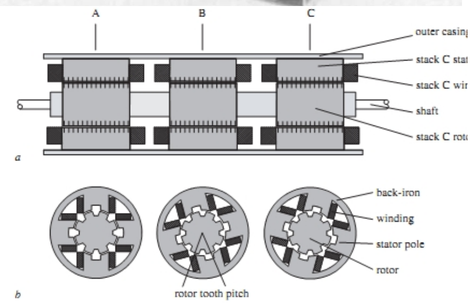
- For each rotor stack, there is a toothed stator segment around it, whose pitch angle is identical to that of the rotor ($\theta s = \theta r$).
- A stator segment may appear to be similar to that of an equal-pitch single-stack stepper, but this is not the case.
- Each stator segment is wound to a single phase, thus the entire segment can be energized (polarized) or de-energized (depolarized) simultaneously. It follows that, in the equal pitch case,
- Meaning $p = s$; where *p is the # of phases* and *s is the # of rotor stacks*.
- The misalignment that is necessary to produce the motor torque may be introduced in one of two ways:
  1. The teeth in the stator segments are perfectly aligned, but the teeth in the rotor stacks are misaligned consecutively by $1/s$ × pitch angle.
  2. The teeth in the rotor stacks are perfectly aligned, but the teeth in the stator segments are misaligned consecutively by $1/s$ × pitch angle.

- Now consider the three-stack case.
  - Suppose that phase 1 is energized
    - Then the *teeth in the rotor stack 1* will *align perfectly with the stator teeth in phase 1 (segment 1)*.
    - But the teeth in the rotor stack 2 will be shifted from the stator teeth in phase 2 (segment 2) by a one-third-pitch angle in one direction, and
    - The teeth in rotor stack 3 will be shifted from the stator teeth in phase 3 (segment 3) by a *two-thirds pitch angle* in the same direction (or a one-third-pitch angle in the opposite direction).
  - It follows that *if phase 1* is now de-energized and phase 2 is energized:
    - The rotor will turn through one-third pitch in one direction.
    - If, *instead, phase 3* is turned on after phase 1, the *rotor will turn through one-third pitch in the opposite direction*.
    - Clearly, the step angle (for full stepping) is a one-third-pitch angle for the three-stack, three-phase construction.
    - The switching sequence 1-2-3-1 will turn the rotor in one direction,
    - And the switching sequence 1-3-2-1 will turn the rotor in the opposite direction.

In general, for a stepper motor with s stacks of teeth on the rotor shaft, the full-stepping step angle is given by: $\Delta\theta = \frac{\theta}{s} = \frac{\theta}{p}$; where $\theta = \theta r = \theta s =$ tooth pitch angle.

- *Note* that the step angle can be decreased by increasing the number of stacks of rotor teeth.
- Increased number of stacks also means more phase windings with associated increase in the magnetic field and the motor torque.
- However, the length of the motor shaft increases with the number of stacks, and can result in flexural (shaft bending) vibration problems (particularly whirling of the shaft), air gap contact problems, large bearing loads, wear and tear, and increased noise.
- As in the case of a single-stack stepper, half stepping can be accomplished by energizing two phases at a time.
- Hence, in the three-stack stepper, for one direction, the half-stepping sequence is 1-12-2-23-3-31-1;
- In the opposite direction, it is 1-13-3-32-2-21-1.





Unequal-Pitch Multiple-Stack Stepper

- Very *fine angular resolutions (step angles) can be achieved* by this design without compromising the length of the motor.
- In an unequal-pitch stepper motor, *each stator segment has more than one phase (p number of phases).*
- Rather than a simple cascading, however, the phases of different stacks are not wound together and can be switched on and off independently. In this manner yet finer step angles are realized, together with an added benefit of increased torque provided by the multistack design.
- For a *single-stack non-toothed-pole stepper*, we have seen that the step angle is equal to $\theta r - \theta s$.
- In a multistack stepper, this misalignment is further subdivided into ***s*** *equal steps using the interstack misalignment.*
- Hence, the overall step angle for an unequal-pitch, multiple-stack stepper motor with *nontoothed poles* is given by:

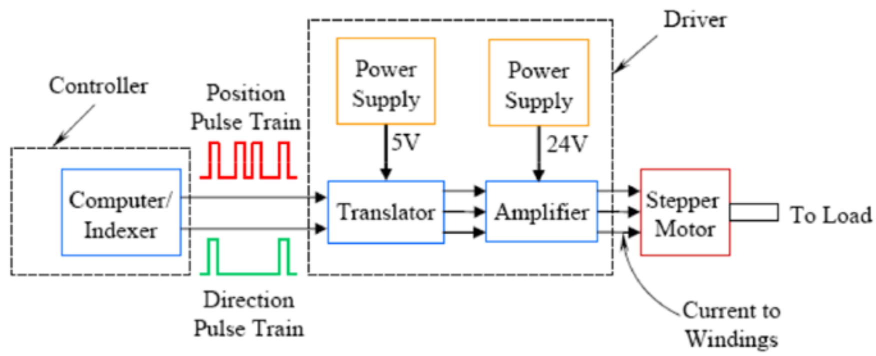
$$\Delta\theta = \frac{\theta_r - \theta_s}{s} \; for \; \theta_r > \theta_s$$

- For a toothed-pole multiple-stack stepper motor, we have:

$$\Delta\theta = \frac{n_s(\theta_r - \theta_{s)}}{mps} \; for \; \theta_r > \theta_s$$

  - *m* is the number of stator poles per phase.
  - p is the number of phases in each stator segment and
  - s is the number of rotor stacks and *s* is the number of rotor stacks.

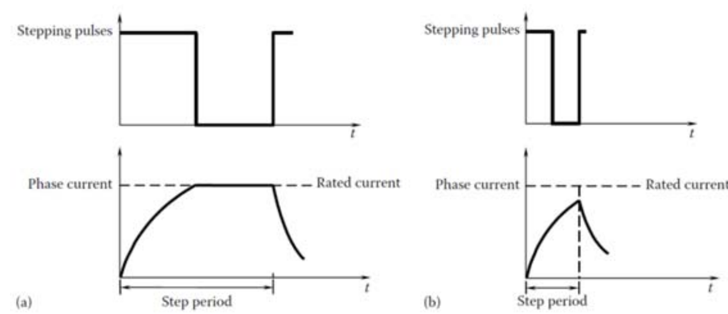
Controller and Driver:



Time Constant and Torque Degradation:

Self inductance is defined as the induction of a voltage in a current-carrying wire when the current in the wire itself is changing. In the case of self-inductance, the magnetic field created by a changing current in the circuit itself induces a voltage in the same circuit. Therefore, the voltage is self-induced.

- As the *torque generated by a stepper motor* **is** *proportional to the phase current*.
- It is desirable for a phase winding to reach its maximum current level as quickly as possible when it is switched on.
- Unfortunately, as a result of *self-induction*, the current in the energized phase does not build up instantaneously when switched on.
- As the stepping rate increases, the time period that is available for each step decreases.
- Consequently, *a phase may be turned off before reaching its desired current level in order to turn on the next phase*, thereby *degrading the generated torque as shown in figure*.
- One way to increase the current level reached by a phase winding would be to simply increase the supply voltage as the stepping rate increases.



Low stepping Rate   Fast stepping rate

- Another approach would be to use a chopper circuit (a switching circuit) to switch on and off at high frequency, a supply voltage that is several times higher than the rated voltage of a phase winding.
- Specifically, *a sensing element (typically, a resistor) in the drive circuit detects the current level and when the desired level is reached, the voltage supply is turned* off.
- When the *current level goes below the rated level, the supply is turned on* again. The required switching rate (chopping rate) is governed by the electrical time constant of the motor. The electrical Time constant is given by: $\tau_e = \frac{L}{R}$

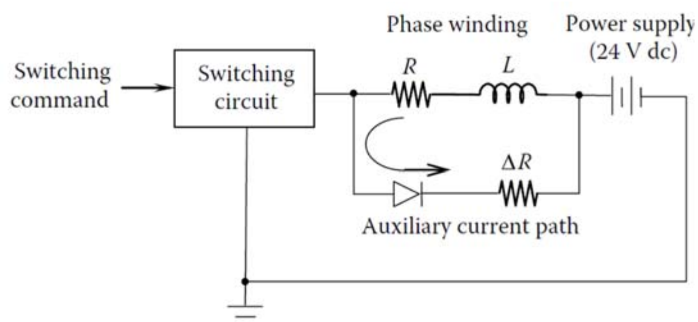
L- Inductance of the energized phase winding
R - Resistance of the energized circuit, including winding resistance

The current increase (build-up) equation is given by: $i = \frac{v}{R}\exp\left(1 - \frac{t}{\tau_e}\right);\ \tau_e = \frac{L}{R}$

- The larger the electrical time constant the slower the current buildup.
- The driving torque of the motor decreases due to the lower phase current.
- Also, because of self-induction, the current does not die out instantaneously when the phase is switched off.

- The *torque characteristics of a stepper motor can be improved (particularly at high stepping rates)* and *the harmful effects of induced voltages can be reduced by decreasing the electrical time constant*.

- A convenient way to accomplish this is by increasing the resistance R.



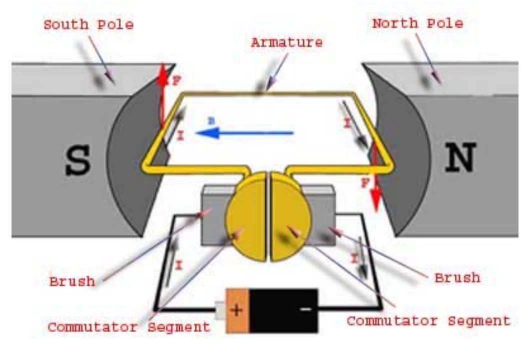
- Note that *we want this increase in R to be effective only during the transient periods (at the instants of switch-on and switch-off).*

- During *the steady period, we like to have a smaller R, which will give a larger current (and magnetic field), producing a higher torque*, and furthermore lower power dissipation (and associated mechanical and thermal problems) and reduction of efficiency.

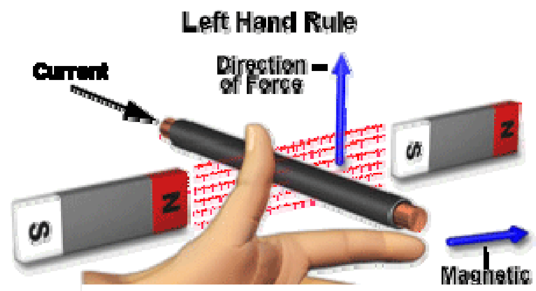
- This can be accomplished by using a diode and a resistor ΔR, connected in parallel with the phase winding, as shown in figure above.

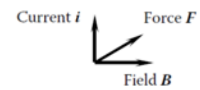
- In this case, *the current will loop through R and ΔR, as shown, during the switch-on and switch-off periods*, thereby decreasing the electrical time constant to: $\tau_e = \frac{L}{R+\Delta R}$

Chapter-9: DC Motors:



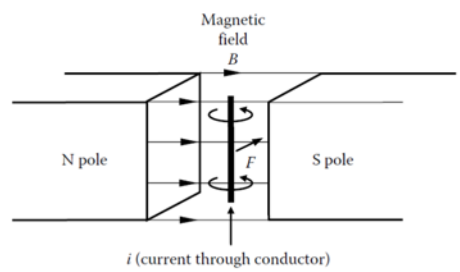
- A dc motor converts dc electrical energy into rotational mechanical energy.
- A major part of the torque generated in the rotor (armature) of the motor is available to drive an external load.
- DC motors are still widely used in numerous engineering applications including robotic manipulators, vehicles, transport mechanisms, disk drives, positioning tables, machine tools, biomedical devices, and servo-valve actuators.
- In view of effective control techniques that have been developed for ac motors, they are rapidly becoming popular in applications where dc motors had dominated. Still, dc motor is the basis of the performance of an ac motor which is judged in such applications.





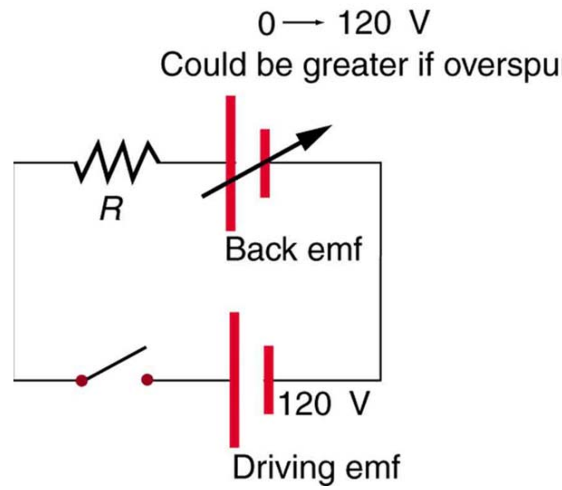
Principle of Operation:

The principle of operation of a dc motor is illustrated in figure shown.



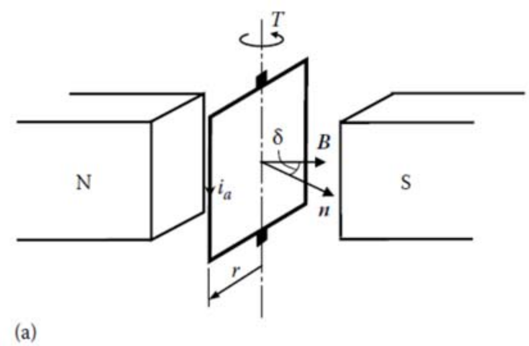
- Consider an *electric conductor placed in a steady magnetic field at right angles to the direction of the field*.
- Flux density B is assumed constant.
- If a *dc current is passed through the conductor*, the *magnetic flux is formed due to the current* loops around the conductor, as shown in the figure.
- Consider a plane through the conductor, parallel to the direction of flux of the magnet.
- On one side of this plane, the current flux and the field flux are additive; on the opposite side, the two magnetic fluxes oppose each other. As a result, an imbalance magnetic force F is generated on the conductor, normal to the plane.
- This force (Lorentz's force) is given by the Lorentz's law: $F = B\,i\,l$
    - B is the flux density of the original field,
    - i is the current through the conductor and
    - l is the length of the conductor
- The active components of i, B, and F are mutually perpendicular and form a right-hand triad, as shown in figure. OR In other words, *in the vector representation of these three quantities*, the vector F can be interpreted as the cross product of the vectors **i** and **B**. Specifically, **F** = **i** × **B**.

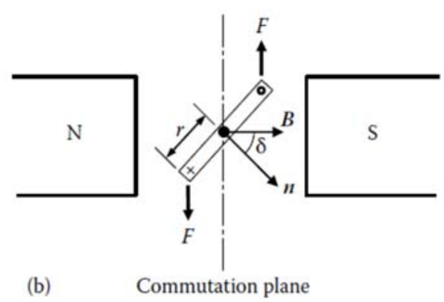
- If the conductor is free to move, the generated force moves it at some velocity ***v*** in the direction of the force.
- As a result of this motion in the magnetic field **B**, a voltage is induced in the conductor. *This is known as the back electromotive force or back e.m.f.*, and is given by: $v_b = Blv$
- According to Lenz's law, the flux due to the back e.m.f. v_b opposes the flux due to the original current through the conductor, thereby trying to stop the motion. This is *the cause of electrical damping* in motors.



Static Torque Characteristics:

For static torque we *assume that the motor speed is low so that the dynamic effects need not be explicitly included* in the discussion.





- Consider a two-pole permanent magnet stator and a planar coil that is free to rotate about the motor axis, as shown in figure-a.
- The coil (rotor, armature) is energized by current i_a as shown.
- The flux density vector of the stator magnetic field is **B** and the unit vector normal to the plane of the coil is **n**.
- The angle between **B** and **n** is *δ, which is known as the torque angle*.
- It should be clear from figure-b that the torque T generated in the rotor is given by T = F × 2r sin δ.
- Which becomes T = Bi_al × 2r sin δ, or
- $T = A\, i_a B\, Sin\, \delta$;
    - *l* is the axial length of the rotor
    - *r* is the radius of the rotor
    - *A* is the face area of the planar rotor