Actuation systems

PART I. Electric Actuation Systems.

- All based on fundamental law (Lorentz's force law) that relates the force in conductors to current and the external magnetic field:

\[ \vec{F} = I \times \vec{B} \]  
(for unit length)

- Follows the Right-hand rule

- Basic actuators: solenoids & relays.

- Solenoids: Coil + Movable iron core (armature)

  Usually good for ON-OFF applications (home appliances, auto, processing plants, fluid power, etc.)

- Relays: A solenoid that opens or closes contacts between electrical leads. Used often for ON-OFF application (large currents).
Voice coil: a coil that can move in a magnetic field. Normally, the magnetic field is generated by permanent magnets and intensified by the iron core. Low weight/low inertia ⇒ good for some applications: audio speakers or hard disk read-write head.

Electric Motors

Normally classified based on their structure (DC, AC, etc.), but can be classified based on function, as well (servo, torque, gear, stepping, ...)

- A typical electric motor has a "rotor" and a "stator." The "winding" is normally wound around an "iron core" forming the "field coils." There is a small air gap between the rotor and the stator poles. In DC motors, a commutator changes the direction of the current (using "brushes") allowing continuous motion. Conducting coils around core also called "armature."

- A permanent magnet can also replace the field coils.

General Motor Types:

- DC Brushed
- AC Synchronous
- Brushless Asynchronous (Induction)
- Universal
Brushless motors (DC) have a variable or rotating magnetic field.

Example of the field-current interaction:

- Thinner gap increases the field

**Typical field-current interaction**

A six-winding commutator

Motor construction & Terminology

Torque output as the number of commutation segments increase:

- Torque ripples get smaller as the # poles increases, as well.
AC machines do not need the commutation as the magnetic field rotates around the stator (due to the AC voltage variations). In "synchronous AC motors," there is current through windings of the rotor, but the induction AC "motors do not have windings. The voltage is induced by variable field, therefore the rotor stays behind and "slips."

In terms of application, it is important to have a detailed look at the speed-torque requirements, but overall, DC motors provide for most of mechatronic applications since they have features suitable for servo control applications. AC servo motors are common in larger sizes.

<table>
<thead>
<tr>
<th>DC</th>
<th>AC</th>
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<tbody>
<tr>
<td>+ Smooth speed control</td>
<td>+ Low cost</td>
</tr>
<tr>
<td>+ Reverse direction</td>
<td>+ constant speed applications</td>
</tr>
<tr>
<td>+ Torque to rotor inertia is high</td>
<td>+ low maintenance (partial Ind. motors)</td>
</tr>
<tr>
<td>+ Respond quickly</td>
<td>+ some new servos are using AC motors and change the frequency to control speed, but the drive electronics becomes expensive.</td>
</tr>
<tr>
<td>+ Dynamic braking or regenerative braking</td>
<td>- Not common for precision</td>
</tr>
<tr>
<td>- More expensive</td>
<td>position control</td>
</tr>
<tr>
<td>- Need sensors</td>
<td></td>
</tr>
<tr>
<td>+ high stall torque (and at low speeds)</td>
<td></td>
</tr>
<tr>
<td>+ can overload the motor (peak/continuous)</td>
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</table>
Torque speed curve for DC motors

The T-W curve is an important characteristic of a motor and depends on the design of the motor. Normally, these curves are given at the rated voltage. Back emf is the voltage induced by the moving rotor field on the poles, which affects the T-W behavior as well.

DC Motor types:
- Permanent magnet (PM DC motors)
- DC shunt, series, or compound motors.

- Stall torque \( T_s \), max torque at zero speed.
- Max Speed \( \omega_{\text{max}} \) (when \( T=0 \)), not really attainable

Q: Why is there an \( \omega_{\text{max}} \) and we cannot accelerate anymore?

See the Figures [10.11 to 10.15] for some of these curves. The torque speed curves in the catalogues normally show the maximum available. Any torque requested under that curve is usually available through controlling the voltage. PM motors deliver a linear relationship between torque & current ⇒ attractive for control.
10.5 DC Motors

Figure 10.11 Motor torque-speed curve.

Figure 10.12 DC permanent magnet motor schematic and torque-speed curve.

Figure 10.13 DC shunt motor schematic and torque-speed curve.

Figure 10.14 DC series motor schematic and torque-speed curve.

Figure 10.15 DC compound motor schematic and torque-speed curve.
PM
+ no need for current (3F)
+ less IR loss
+ good power/mass
+ easy to reverse
+ linear T-I curve
  ↓ easy control
- limited horse power (5hp)
  (brushed/brushless/stepper)

<table>
<thead>
<tr>
<th>Shunt wound</th>
<th>Series wound</th>
<th>Compound wound</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ constant torque-speed</td>
<td>+ high starting torque</td>
<td>+ limits the speed</td>
</tr>
<tr>
<td>- lower starting torque compared to others</td>
<td>+ high speed</td>
<td>- less efficient in constant-speed characteristics</td>
</tr>
<tr>
<td>- harder to control</td>
<td>- run away speed</td>
<td></td>
</tr>
</tbody>
</table>

(Manual setting of the pot is a good application)

Go to [www.epanorama.net/motorcontrol.html](http://www.epanorama.net/motorcontrol.html) for a good comparison and some basic descriptions.

**DC motor model**

\[ V_{emf} = k_e w \quad (1) \]

\[ V_{in} = L \frac{dI_m}{dt} + RI_{in} + k_e w \quad (2) \]

For permanent magnets: \[ T = k_t I_{in} \quad (3) \]

\[ T = (J_a + J_L) \frac{d\omega}{dt} + T_f + T_L \quad (4) \]

⇒ \[ T = (J_a + J_L) \frac{d\omega}{dt} + T_f + T_L \]

- \[ \text{torque constant} \]
- \[ \text{load} \]

- \[ \text{friction} \]
- \[ \text{inertia} \]
with a constant \( V_{in} \) voltage, the motor reaches a steady state speed, where friction and load torques balance the motor torque. Therefore for steady state:

\[
V_{in} = R \, I_{in} + k_e \omega 
\]  \hspace{1cm} (5)

replace \( I_{in} \) from (3) in (5)

\[
V_{in} = \left( \frac{R}{k_e} \right) T + k_e \omega 
\]  \Rightarrow  \hspace{1cm} T = \frac{k_e}{R} V_{in} - \frac{k_e k_T}{R} \omega 
\]  \hspace{1cm} (6)

or

\[
T(w) = T_s \left( 1 - \frac{w}{w_{max}} \right) \]  \hspace{1cm} (7)

\[
T_s = \frac{k_T}{k_e} V_{in} \quad \text{(stall torque)}
\]

\[
w_{max} = \frac{T_s R}{k_e k_T}
\]  \hspace{1cm} (8)

\[
P(w) = T(w) \cdot \omega
\]

\[
P(w) = \omega T_s \left( 1 - \frac{w}{w_{max}} \right)
\]  \hspace{1cm} (9)

\[
P_{max}: \quad \frac{dP}{dw} = 0 \Rightarrow \quad T_s \left( 1 - \frac{2w}{w_{max}} \right) = 0 \Rightarrow \quad \omega^* = \frac{1}{2} w_{max}
\]  \hspace{1cm} (10)

Also note that stall current is

\[
I_s = \frac{V_{in}}{R}
\]
Electronic control of PMDC motors

- **Objective**: in automatic control, the voltage needs to be varied automatically to control speed or position. Normally, the motors will work with a sensor to achieve that.

- Voltage controllers are:
  - Regular Linear amplifiers
  - Pulsewidth modulators, (PWM) (FETS, BPS)

- **PWM** allows only ON-OFF operations of the transistors which operate in efficient modes (less heat generated) ⇒ less loss.

Power amplifiers or servo amplifiers, based on PWM dominate the market:

- Low cost
- Low power requirement
- Ease of design
- Small size and weight.
PWM operates on a fixed frequency $f$ (very high, in kHz range). Turns the $V_{in}$ ON and OFF at that frequency. The average voltage is controlled using the time the voltage is ON.

\[
duty\ cycle = \frac{ON\ time}{T_{period}} = \frac{t}{T} (\%)
\]

\[
T = \frac{1}{f}
\]
\[
t = ON\ time
\]

$0 < t < T$

Example: PWM drive unit.

In the motor, due to resistance & Inductance, there is a response time.

In reality, what we are interested in controlling is the current (torque). Therefore, lots of amplifiers operate in current (torque) mode. They control the current in the loop through voltage.
One can buy these PWM generators as a COTS solution:

Simply arrange 4 transistors in an H configuration:

(Q₁ & Q₄) turn on together & (Q₂ & Q₃) together (alternate)

→ A simple way to modulate a command signal into PWM.

You can buy the whole Amplifier/PWM check
Advanced Motion Control for a range of products
or Elmo Drives
or MAXON MOTORS
Brushless DC motor (PM DC)

- no need for commutation (done electronically) (+)
- permanent magnet on the rotor
- stator changes the field (rotates it)
- needs a sensor to do electronic commutation (—) (Normally Hall-effect or resolvers or encoders)
- needs to control 3 phases separately ⇒ complex drive (—)
- lower weight/power (+)
- less maintenance (+)
- more expensive (—)
- high speeds (+)

It normally uses a three-phase stator with three current controllers.
It uses a bridge with 6 transistors.

Total torque = Ta + Tbr + Tc = i_d k_T 8.8 + i_b k_b / (B1 r_0) + i_c k_c / (B2 r_0)

\[ i_d \sin \theta \Rightarrow T_b = k_T i_d \] again linear ⇒ use if the same way for control.
Stepper Motors

- Stepper motors (or step motors) are able to position their rotor at a number of preset discrete locations as a result of input pulses. They provide mechanical steps. (~)

- They normally do not need a sensor for feedback, whereas a servo motor does need a sensor feedback for proper position control. Having a feedback is optional for step motors. (~)

- They are cheaper, simple, and rugged. Power usually < 1 HP.

- Example of how it operates: a four-pole stator & PM rotor.

\[\text{Diagram of step operations} \]

(step 0): stable \hspace{1cm} \text{transition} \hspace{1cm} \text{unstable} \hspace{1cm} \text{step 1} \hspace{1cm} \text{stable} \hspace{1cm} \text{unstable} \]
• As long as the stepper motor is in a stable position it can stand a torque called "holding torque".

• Successive change of polarity of the poles will result in stepping motion.

• Depending on the load inertia and speed, the steps might pass the desired number of steps (careful when using with heavy loads). The motor slips.

If the stepper motor moves fast, then it does not stop at equilibrium points resulting in almost continuous motion. If the speed is high enough, the stepper motor will go to "slewing mode" as opposed to "locked step mode". In the "locked step mode" the step integrity is not compromised, but in "slewing mode" the motor might slip allowing positioning error.
Field coil schematic for a stepper motor:

- Bipolar uses two power sources
- Unipolar uses a single power source.

Then a combination of ON & OFF states for phases $\phi_1, \phi_2, \phi_3,$ and $\phi_4$ can drive the motor.

Note: Holding torque is less at half steps.

In “Micro-stepping”, different levels of current (instead of ON/OFF) are used to create more in-between steps to increase resolution.
Motor selection

1. Motor should be able to accelerate the load:

\[
\frac{T_{\text{motor}} - T_{\text{load}}}{J} = \alpha \ \text{rad/s}^2.
\]
Particularly, this is important for starting the motion (high friction).

2. Maximum speed. When operating at maximum speed, no torque is available \(\Rightarrow\) not achievable when loaded.

3. General form of the curve:
   when the requested torques is against the direction of motion, max torque is always achievable.

4. Duty cycle: \(\eta = \frac{\Delta T_{\text{loaded}}}{\Delta T_{\text{total}}}\) if \(\eta < 1\) \(\Rightarrow\) lower power motor can be used, i.e., can get more torque than the continuous torque.

\[\text{If } \Delta T_{\text{loaded}} \text{ is very long } \Rightarrow \text{ may not use it, why?} \]
shouldn't pick a weaker motor or it may burn.

5. How much power?
   Again, the motor power and load requirement should match (taking the duty cycle into consideration).
6. Availability of the power source: DC/AC, battery, etc.

7. Load inertia affects the time response. To meet the time response characteristics, you need more powerful motors.

8. Is it a constant-speed application? ⇒ AC synchronous or DC-shunt would be good.

9. Accurate positioning?
   - Less load, low speeds ⇒ stepper motor
   - Higher loads ⇒ feedback control (servo motor).

10. Transmission:

    ![Diagram of motor, gear, and load]

    The inertia of the load reflected on the motor side is divided by $N^2$.
    $$J = J_m + \frac{J_L}{N^2}$$
    or from the load-side:
    $$J_{eff} = J_m N^2 + J_L.$$  

    In the meantime, the speed at the motor will be very high if $N$ is selected too high, therefore less available torque. A trade-off study needed to select gear ratios.

11. Matching the "load line" & motor torque-speed curve, if possible. Also if a nominal speed needed, then match the operating speed.

    manifold of constraints.