Fundamentals of Motor Control

Industrial & Power conversion Training
Agenda

1. Basic principle
2. Brush DC motor
3. Three-phase brushless DC motor
4. Bipolar stepper motor
Basic principle
An electric motor is a device converting electrical energy into mechanical energy (generally a torque).

This conversion is usually obtained through the generation of a magnetic field by means of a current flowing into one or more coils.
The rotation is obtained thanks to the attractive force between two magnetic fields:

- One field is located on the rotor (the moving part).
- The second magnetic field is located on the stator (the body of the motor).

Usually one of the two is generated by a permanent magnet while the other one is generated through an electromagnet (solenoid).
The relation between electrical energy (current) and magnetic field generated by a solenoid (coil) is obtained through the following formula:

\[ B = k \cdot I_{ph} \]
The output torque of an electrical motor depends on the intensity of the rotor and stator magnetic fields and on their phase relation:

\[ Tq \propto B_{rot} \cdot B_{sta} \cdot \sin(\theta) \propto I_{ph} \cdot \sin(\theta) \]

The angle \( \theta \) between the two magnetic field is named load angle. The maximum output torque, and then the maximum efficiency, is obtained when the load angle is 90°.
The rotation of the rotor magnetic field ($B_{\text{rot}}$) causes a variation of the magnetic flux in the solenoid.

Consequently an electro-motive force facing the flux variation is generated (Lenz’s law). This effect is named **back electro-motive force** (aka BEMF) and it is proportional to the motor speed according to the formula:

$$V_{\text{BEMF}} = k_e \cdot \text{Speed}$$
The electric motor operation is based on the following points:

- At least one of the two **magnetic field** is generated by a solenoid carrying a current.
- **Phase relation** between the rotor and stator magnetic field (i.e. the load angle) must be always greater than 0° in order to keep the motor in motion (negative angles reverse the rotation).
- Output **torque** depends to both solenoid **current** and **load angle**.
- Motor rotation causes a **back electro-motive** force opposing the motion itself.
An inductive load (motor phases included) can be represented as an LR series which stores energy in the form of current.

Applying a voltage to the load it is possible to change the amount of current stored into the inductance.
Charge and discharge of an inductive load

Scenario 1 (ON time)
Inductance is charged applying a voltage:

\[ i(t) = \frac{V_S}{R} + \left( i(0) - \frac{V_S}{R} \right) \cdot e^{-t \cdot R/L} \]

Scenario 2 (slow decay)
Inductance is discharged shorting the leads:

\[ i(t) = i(0) \cdot e^{-t \cdot R/L} \]

Scenario 3 (fast decay)
Inductance is discharged applying a voltage:

\[ i(t) = -\frac{V_S}{R} + \left( i(0) + \frac{V_S}{R} \right) \cdot e^{-t \cdot R/L} \]

NOTE: \( i(0) \) is the starting current
The most common method to control the current is the **fixed OFF time** method. It is a **closed-loop** approach which implies the measurement of the controlled current.

Both PWM frequency and duty-cycle changes according to the target current and boundary conditions.
How to read the load current?

When the low side switch is ON, the load’s current flows through the resistor positioned in-between the low side and the ground.

The resulting voltage drop is proportional to the current:

\[ V_{\text{SENSE}} = i_{\text{load}} \cdot R_{\text{SENSE}} \]

This resistor is named **shunt resistor** or **sense resistor**.
According to the current direction the drop on the sense resistor can be both positive or negative. Reading negative voltages requires specific signal conditioning circuitry.

The simplest current control algorithms senses the current in one direction only.

In some cases, the current doesn’t flow into the shunt resistor even if the low side switch is on. 

\[ V_{SENSE} = 0 \]
The **back electromotive force** can change the behavior of the system.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>BEMF &gt; 0</th>
<th>BEMF &lt; 0</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td>The BEMF slows the current increase because it opposes to the VS voltage</td>
<td>The BEMF is added to the VS to increase the current</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td>The BEMF increases the current drop</td>
<td>The BEMF reduces the current drop</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td>The BEMF is added to the VS to decrease the current</td>
<td>The BEMF opposes to the VS voltage slowing the current drop</td>
</tr>
</tbody>
</table>
Brush DC motor
The stator magnetic field is generated by a permanent magnet.

The rotor is composed by a group of coils.

The rotor coils are sequentially connected to the motor leads through mechanical switches (brushes).
Forcing a current in the motor leads the rotor magnetic field is generated. The torque applied to the rotor is the highest possible because the load angle ($\theta$) is about 90°.
The brushes connect the motor leads to the next coil (B) keeping the load angle almost equal to 90° during rotation.
Changing the current direction the motor rotation is reversed.
Brush DC motor

Basics – electrical model

Phase impedance

\[ Z_{ph} = R_{ph} + j\omega L_{ph} \]

Back electromotive force generator

\[ V_{BEMF} = k_e \cdot \text{Speed} \]
Brush DC motor

Voltage mode driving

- $V_{motor}$
- $V_{BEMF}$
- $I_{motor}$
- $T_{q_{load}}$
- $T_{q_{motor}}$

Operating point
Increasing the supply voltage allows reaching higher speed but the current rating of the motor is exceeded during the ramp-up.
Using a current limiter it is possible to extend the speed range without exceeding the current rating of the motor.

\[ V_{\text{ph}} = 10 \text{ V} + \text{current limiter} \]
• The magnetic field intensity is proportional to the current forced into the motor leads.
• The magnetic field rotation is automatically obtained commutating the active coil through mechanical switches (brushes).
• The load angle is almost constant, and it is about 90° allowing the maximum efficiency (current vs. torque proportion).
• The motor is controlled applying a voltage on the motor leads. The higher the voltage, the higher the speed. The direction is changed reversing the polarity on the leads.
• The maximum torque is limited by the current rating of the motor and it is obtained at zero speed (start-up).
• The maximum speed is limited by the supply voltage and it is obtained when no load torque is present.
Three-phase brushless DC motor
There are different types of brushless motors:

- Single phase
- Two phase
- Three phase

The presentation will describe the basics of the three-phase brushless motor because it is the most common version.

Anyway most of the considerations can be extended to the other types.
Three-phase brushless DC motor

Basics - mechanical

A permanent magnet generates the magnetic field of the rotor

The stator is composed by three coils, named phases, positioned at 120° from each other

The windings are connected by one of the sides. The sum of the currents is zero
The **rotor magnetic field** is always present, and it is generated by a permanent magnet.

When a current flows from a motor phase to another one the magnetic fields are combined generating the **stator field**.
The torque applied to the motor is proportional to the sine of the load angle ($\theta$).

When the rotor magnetic field approaches the stator one, the torque is reduced.

In order to keep the motor in motion it is necessary to change the direction of the stator magnetic field.
Three-phase brushless DC motor

Basics – electrical model

Phase impedance

\[ Z_{ph} = R_{ph} + j \omega L_{ph} \]

Back electromotive force generators.
BEMFs are three sinewave voltages*(*) delayed from each other by 120°.
The sinewave amplitude is proportional to the motor speed:

\[ V_{BEMF} = k_e \cdot \text{Speed} \]

(*) Some motors have a BEMF with trapezoidal shape instead of sinusoidal
Three-phase brushless DC motor

6-step driving – rotor position

The **6-step driving** imposes a current between two of the three phases leaving the third one floating.

In this way the stator magnetic field can be positioned in 6 **discrete directions**.

The scanning of the 6 driving combinations of the six step is synchronized by the **rotor position**.

The rotor position can be monitored through Hall sensors or using a BEMF sensing technique (sensorless)
Three-phase brushless DC motor

6-step driving – Hall sensors feedback

The Hall sensors detects the rotor position returning a digital or analog signal. The information is used to move the stator magnetic field in the next position.

<table>
<thead>
<tr>
<th>Rotor position</th>
<th>Stator position</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>U → W</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>V → W</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>V → U</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>W → U</td>
</tr>
<tr>
<td>5</td>
<td>E</td>
<td>W → V</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>U → V</td>
</tr>
</tbody>
</table>

NOTE: Clockwise rotation
Three-phase brushless DC motor

6-step driving – current waveforms

$I_U$

$I_V$

$I_W$
The sensorless driving detects the BEMF zero-crossing measuring the voltage on the floating phase.

When the magnetic field of the rotor crosses the unloaded phase, the respective BEMF voltage changes polarity (zero-crossing)
Three-phase brushless DC motor

6-step driving – electrical model

In order to detect the zero-crossing of the BEMF the center-tap voltage must be known. Some motors makes the center tap available. In other cases it can be reconstructed through the phase voltages.
The Field Oriented Control (FOC) algorithm allows to obtain the maximum performance from a BLDC motor.

The objective of the algorithm is to control the vector components of the stator magnetic field (i.e. the phase currents) in order to obtain the target **intensity** and **phase relation** with the rotor magnetic field.
The **Field Oriented Control (FOC)** can be represented through this block diagram.
Three-phase brushless DC motor

Field Oriented Control – pro & cons

**Pros**

- Can control the **efficiency** of the system imposing a **load angle** (direct component of the current)
- **Smooth operation** thanks to the sinusoidal driving

**Cons**

- Implies **complex calculations** which cannot be performed by low level microcontrollers
- Needs the **information** of the rotor flux (i.e. expensive sensors or more complex calculations)
The stator magnetic field is the combination of the magnetic fields generated by the motor phases.

The magnetic field rotation is obtained driving in the proper way the phases.

The position of the rotor must be sensed in order to determine the proper driving sequence.
Bipolar stepper motor
There are different types of stepper motors:

- Unipolar (two phases)
- **Bipolar (two phases)**
- Three phase
- Five phase

The presentation will describe the basics of the bipolar stepper motor because it is one of the most common version.

Anyway most of the considerations can be extended to the other types.
Bipolar stepper motor

Basics - mechanical

The stator is composed by two coils, named **phases**, positioned at 90° from each other.

The stepper motors are designed to **keep a target angular position**. This objective is obtained splitting the rotation of the shaft in small fractions named **steps**.

Each step represents a stable position where the motor shaft can be easily kept forcing the proper current into the phases.

A permanent magnet generates the magnetic field of the rotor.

NOTE: This is the simplified model of a 4 step/round stepper motor.
The rotor magnetic field is always present, and it is generated by a permanent magnet.

The stator magnetic field is generated forcing a current in one phase.

The rotor will align to the stator magnetic field: **the target step position is achieved.**
Bipolar stepper motor

Basics – step angle

In stepper motors a complete rotation of the stator magnetic field (i.e. a sequence of four steps) does not correspond to a complete mechanical rotation.

This effect is obtained through a proper shaping of the rotor and stator cores: consequently at each position of the magnetic field more mechanical positions correspond.

\[
\text{Step angle} = \frac{360}{\text{poles} \times \text{phases}} = \frac{360}{N_{\text{STEP}}}
\]

Example: in a 20 steps stepper motor each full step combination (numbered from 1 to 4) can position the rotor at 5 possible angles (colors)
The phases have always to be driven following the proper sequence, otherwise the motor rotation cannot be achieved.

The stepper motor is moved performing a series of small rotations, i.e. the steps. This way the mechanical position of the shaft is always known without the need for a dedicated position sensor (*).

The motor speed is determined by the frequency at which the sequence is performed, and it is expressed in steps per second or pulses per second (pps).

(*) This is true only if the starting position is already known.
Back electromotive force generator. BEMF are two sinewave voltages\(^(*)\) delayed from each other by 90°. The sinewave amplitude is proportional to the motor speed:

\[ V_{BEMF} = k_e \cdot \text{Speed} \]
Full-step wave mode

Forcing the phase currents according to the following sequence, the motor rotates performing one step at a time.

This is named Full-step 1 phase on driving or Full-step wave mode

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{phA}$</td>
<td>$+$</td>
<td>$0$</td>
<td>$-$</td>
<td>$0$</td>
</tr>
<tr>
<td>$I_{phB}$</td>
<td>$0$</td>
<td>$+$</td>
<td>$0$</td>
<td>$-$</td>
</tr>
</tbody>
</table>
Bipolar stepper motor

Full-step normal mode

It is also possible to perform the sequence forcing the same current in both the phases. In this case the stator magnetic field is the geometric sum of two components and is $\sqrt{2}$ times stronger.

This is named Full-step 2 phase on driving or Full-step normal mode

<table>
<thead>
<tr>
<th></th>
<th>1b</th>
<th>2b</th>
<th>3b</th>
<th>4b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{phA}$</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>$I_{phB}$</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Bipolar stepper motor

Half step

Combining the two driving methods it is possible to position the rotor in middle position between two subsequent steps.

Half-step is performed.

This method doubles the number of mechanical positions achievable by the motor.

<table>
<thead>
<tr>
<th>1ph ON</th>
<th>2ph ON</th>
<th>Half-step</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1b</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2b</td>
<td>2b</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3b</td>
<td>3b</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>4b</td>
<td>4b</td>
</tr>
</tbody>
</table>
Microstepping

Starting from half-step concept, it is possible to further increase the number of stable mechanical position using the microstepping technique.

Each position of the rotor can be achieved applying the proper pair of currents to the phases.

This pair is determined by the sine and cosine values of the target angle.

\[
I_{phA} = I_{peak} \cdot \sin(\theta)
\]

\[
I_{phB} = I_{peak} \cdot \cos(\theta)
\]
Microstepping - Stall and step-loss

When the stepper motor is loaded with a torque exceeding its torque vs. speed characteristic a **stall** or a **step-loss** events could occur.

The stepper motor is in **stall** when it completely loses the synchronism. As result the rotor is stopped or vibrates, but no rotation is performed.

When a **step-loss** occurs the motor loses the synchronism fro a short period and then resumes.

As result the rotor continues its rotation, but the actual position is different from the ideal one.
Bipolar stepper motor

Torque vs. Speed characteristic

- **Holding torque**: The maximum torque the motor can sustain when stopped.
- **Pull-out torque**: The maximum output torque vs speed when the motor is in motion.
- **Pull-in torque**: The maximum output torque vs speed when the motor starts from the hold condition.
- **Max speed**: The maximum speed the motor can reach when unloaded.

**NOTE**: The curves change with driving method and phase current. Most manufacturers provide the curve at rated current in full-step.
Resonances

Each time a step (or a microstep) is performed, the final position is not immediately asserted, but the rotor vibrates around the target position before stop.

When the step rate reaches the frequency of this vibration, the mechanic of the motor resonates.

This effect is named mid-point resonance.

The stepper motor should not operate in this condition.

Effects of the resonances:
- **Strong vibrations**: the motor is very noisy because the resonances stimulates the internal mechanic.
- **Reduced torque**: the energy is “dissipated” by the resonance (vibrations) so a minor par of the energy is converted into an effective torque.
- **Discontinuous motion**: if vibration are strong enough to move the rotor in the unstable region step-loss events could occurs.
The stepper motor is designed to move the rotor in a target position and keep it.

The stator magnetic filed is the combination of the magnetic fields generated by the motor phases.

Each combination of currents in the motor phases moves and keeps the motor in a stable position. At each position of the magnetic field more mechanical positions may correspond.

The motor rotation is performed through a proper sequence of phase currents.

The rotation is always performed one step (or microstep) at a time.
Thank you