Actuators and Drive Systems

Actuators are one of the key components contained in a robotic system. A robot has many degrees of freedom, each of which is a servoed joint generating desired motion. We begin with basic actuator characteristics and drive amplifiers to understand behaviour of servoed joints.

An actuator is a component of a machine that is responsible for moving and controlling a mechanism or system, for example by opening a valve. In simple terms, it is a "mover".

An actuator requires a control signal and a source of energy. The control signal is relatively low energy and may be electric voltage or current, pneumatic or hydraulic pressure, or even human power. Its main energy source may be an electric current, hydraulic fluid pressure, or pneumatic pressure. When it receives a control signal, an actuator responds by converting the signal's energy into mechanical motion.

An actuator is the mechanism by which a control system acts upon an environment. The control system can be simple (a fixed mechanical or electronic system), software-based (e.g. a printer driver, robot control system), a human, or any other input

Most of today's robotic systems are powered by electric servomotors. Therefore, we focus on electromechanical actuators.

2.1 DC Motors

Figure 2.1 illustrates the construction of a DC servomotor, consisting of a stator, a rotor, and a commutation mechanism. The stator consists of permanent magnets, creating a magnetic field in the air gap between the rotor and the stator. The rotor has several windings arranged symmetrically around the motor shaft. An electric current applied to the motor is delivered to individual windings through the brush-commutation mechanism, as shown in the figure. As the rotor rotates the polarity of the current flowing to the individual windings is altered. This allows the rotor to rotate continually.

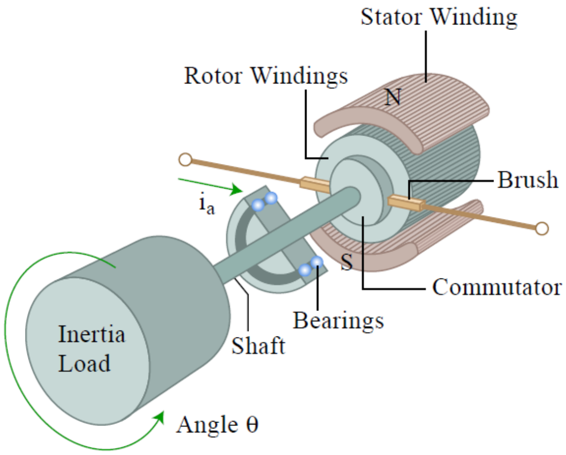

Figure 2.1 Construction of a DC Motor

Let τ_m be the torque created at the air gap, and i the current flowing to the rotor windings. The torque is in general proportional to the current, and is given by

$\tau_m = K t \cdot i$ eq 1

where the proportionality constant is called the ***torque constant,*** one of the key parameters describing the characteristics of a DC motor. The torque constant is determined by the strength of the magnetic field, the number of turns of the windings, the effective area of the air gap, the radius of the rotor, and other parameters associated with materials properties. *Kt*

In an attempt to derive other characteristics of a DC motor, let us first consider an idealized energy transducer having no power loss in converting electric power into mechanical power. Let E be the voltage applied to the idealized transducer. The electric power is then given by $E.i$, which must be equivalent to the mechanical power:

$$P_{in} - E.i = \tau_m \,.\, \omega_m \qquad \text{eq 2}$$

where ωm is the angular velocity of the motor rotor. Substituting eq.(1) into eq.(2) and dividing both sides by i yield the second fundamental relationship of a DC motor:

$$E = K_t .\, \omega_m \qquad \text{eq 3}$$

The above expression dictates that the voltage across the idealized power transducer is proportional to the angular velocity and that the proportionality constant is the same as the torque constant given by eq.(1). This voltage E is called the back emf (electro-motive force) generated at the air gap, and the proportionality constant is often called the back emf constant.

NB: Based on eq.(1), the unit of the torque constant is *Nm/A* in the metric system, whereas the one of the back emf constant is *V/rad/s* based on eq.(2).

The actual DC motor is not a loss-less transducer, having resistance at the rotor windings and the commutation mechanism. Furthermore, windings may exhibit some inductance, which stores energy. Figure 2.1.2 shows the schematic of the electric circuit, including the windings resistance *R* and inductance *L*. From the figure,

$$U = R \,.\, i + L\frac{di}{dt} + E \qquad eq\ 4$$

where *u* is the voltage applied to the armature of the motor.

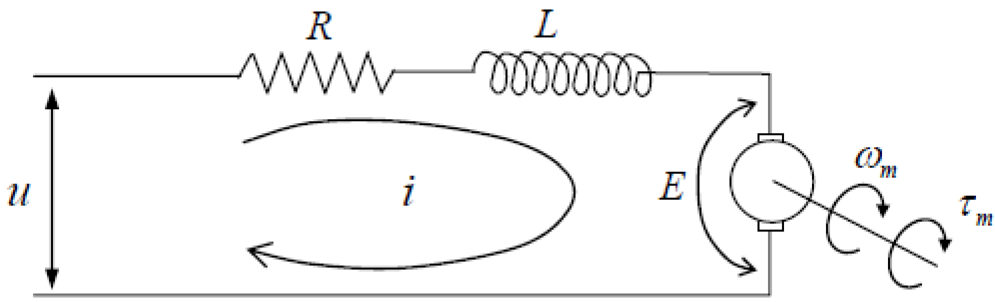

Fig 2.2 Electric Circuit Armature

Combining eqs.(1), (3) and (4), we can obtain the actual relationship among the applied voltage *u,* the rotor angular velocity ω_m, and the motor torque τ_m.

$$\frac{K_t}{R}u = \tau_m + T_e\frac{d\tau_m}{dt} + \frac{{K_t}^2}{R}\,\omega_m \qquad eq\ 5$$

where time constant $Te = \frac{L}{R}$, called the motor reactance, is often negligibly small. Neglecting this second term, the above equation reduces to an algebraic relationship:

$$\tau_m = \frac{K_t}{R}u - \frac{{K_t}^2}{R}\,\omega_m \qquad eq\ 6$$

This is called the torque-speed characteristic. Note that the motor torque increases in proportion to the applied voltage, but the net torque reduces as the angular velocity increases. Figure 2.3 illustrates the torque-speed characteristics. The negative slope of the straight lines, - $\frac{{K_t}^2}{R}$, implies that the voltage-controlled DC motor has an inherent damping in its mechanical behaviour.

The power dissipated in the DC motor is given by

$$P_{dis} = R\,.\,i^2 = \frac{R}{{K_t}^2}{\tau_m}^2 \qquad \text{eq 7}$$

from eq.(1). Taking the square root of both sides yields

$$\sqrt{P_{dis}} = \frac{\tau_m}{K_m}, K_m = \frac{K_t}{\sqrt{R}} \qquad eq8$$

where the parameter is called the motor constant. The motor constant represents how effectively electric power is converted to torque. The larger the motor constant becomes, the larger the output torque is generated with less power dissipation. A DC motor with more powerful magnets, thicker winding wires, and a larger rotor diameter has a larger motor constant. A motor with a larger motor constant, however, has a larger damping, as the negative slope of the torque-speed characteristics becomes steeper, as illustrated in Figure 2.3.

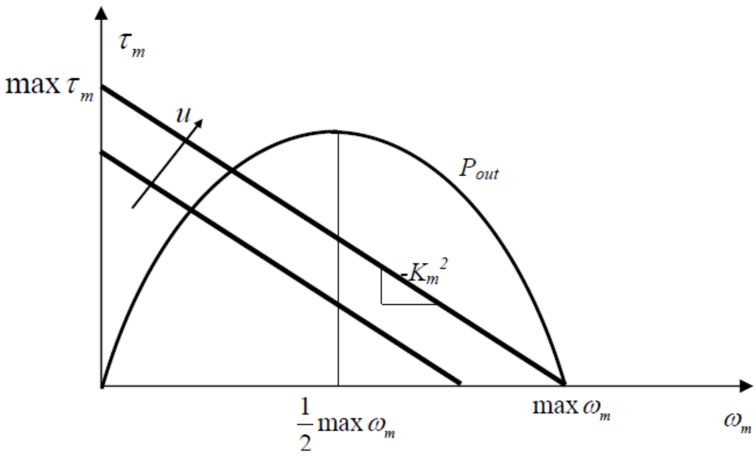

Figure 2.3 Torque-speed characteristics and output power

Taking into account the internal power dissipation, the net output power of the DC motor is given by

$$P_{out} = \tau_m \, . \, \omega_m = \left(\frac{K_t}{R}u - K_m^2 . \omega_m\right)\omega_m \qquad \text{eq 9}$$

This net output power is a parabolic function of the angular velocity, as illustrated in Figure 2.3. It should be noted that the net output power becomes maximum in the middle point of the velocity axis, i.e. 50 % of the maximum angular velocity for a given armature voltage *u*. This implies that the motor is operated most effectively at 50 % of the maximum speed. As the speed departs from this middle point, the net output power decreases, and it vanishes at the zero speed as well as at the maximum speed. Therefore, it is important to select the motor and gearing combination so that the maximum of power transfer be achieved.

2.2 Power Electronics

Performance of servomotors used for robotics applications highly depends on electric power amplifiers and control electronics, broadly termed ***power electronics***. Power electronics has shown rapid progress in the last two decades, as semiconductors became faster, more powerful, and more efficient. In this section we will briefly summarize power electronics relevant to robotic system development.

2.2.1 Pulse width modulation (PWM)

In many robotics applications, actuators must be controlled precisely so that desired motions of arms and legs may be attained. This requires a power amplifier to drive a desired level of voltage (or current indirectly) to the motor armature. Use of a linear amplifier (like an operational amplifier), however, is power-inefficient and impractical, since it entails a large amount of power loss. Consider a simple circuit consisting of a single transistor for controlling the armature voltage, as shown in Figure 2.4

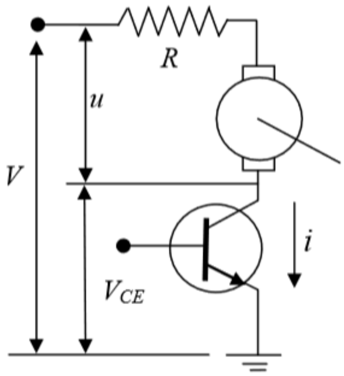

Fig 2.4 Analogue power amplifier for driving the armature voltage

Let V be the supply voltage connected to one end of the motor armature. The other end of the armature is connected to the collector of the transistor. As the base voltage varies the emitter-collector voltage varies, and thereby the voltage drop across the motor armature, denoted *u* in the figure, varies accordingly. Let *i* be the collector current flowing through the transistor. Then the power loss that is dissipated at the transistor is given by

$$P_{loss} = (V - u)\,.\,i = \frac{1}{R}(V - u)\,.\,u \qquad \text{eqn 10}$$

where R is the armature resistance. Figure 2.5 plots the internal power loss at the transistor against the armature voltage. The power loss becomes the largest in the middle, where half the supply voltage *V/2* acts on the armature. This large heat loss is not only wasteful but also harmful, burning the transistor in the worst case scenario. Therefore, this type of linear power amplifier is seldom used except for driving very small motors.

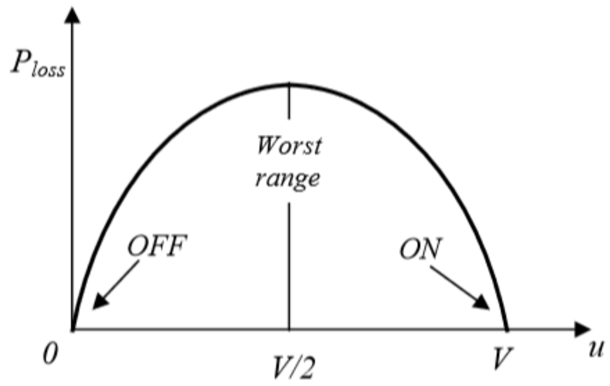

Fig 2.5 Power loss at the transistor vs. the armature voltage.

An alternative is to control the voltage via ON-OFF switching. Pulse Width Modulation, or PWM for short, is the most commonly used method for varying the average voltage to the motor. In Figure 2.5 it is clear that the heat loss is zero when the armature voltage is either 0 or V. This means that the transistor is completely shutting down the current (OFF) or completely admitting the current (ON). For all armature voltages other than these complete ON-OFF states, some fraction of power is dissipated in the transistor. Pulse Width Modulation (PWM) is a technique to control an effective armature voltage by using the ON-OFF switching alone. It varies the ratio of time length of the complete ON state to the complete OFF state. Figure 2.6 illustrates PWM signals. A single cycle of ON and OFF states is called the PWM period, whereas the percentage of the ON state in a single period is called duty rate. The first PWM signal is of 60% duty, and the second one is 25 %. If the supply voltage is V=10 volts, the average voltage is 6 volts and 2.5 volts, respectively.

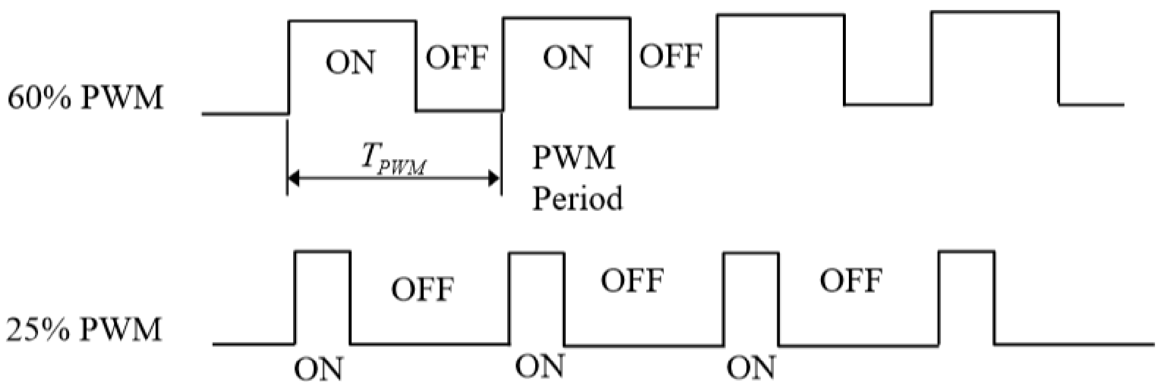

Fig 2.6 Pulse width modulation

The PWM period is set to be much shorter than the time constant associated with the mechanical motion. The PWM frequency, that is the reciprocal to the PWM period, is usually

2 ~ 20 kHz, whereas the bandwidth of a motion control system is at most 100 Hz. Therefore, the discrete switching does not influence the mechanical motion in most cases.

As modeled in eq.(4), the actual rotor windings have some inductance *L*. If the electric time constant *Te* is much larger than the PWM period, the actual current flowing to the motor armature is a smooth curve, as illustrated in Figure 2.7(a). In other words, the inductance works as a low-pass filter, filtering out the sharp ON-OFF profile of the input voltage. In contrast, if the electric time constant is too small, compared to the PWM period, the current profile becomes zigzag, following the rectangular voltage profile, as shown in Figure 2.7(b). As a result, unwanted high frequency vibrations are generated at the motor rotor. This happens for some types of pancake motors with low inductance and low rotor inertia.

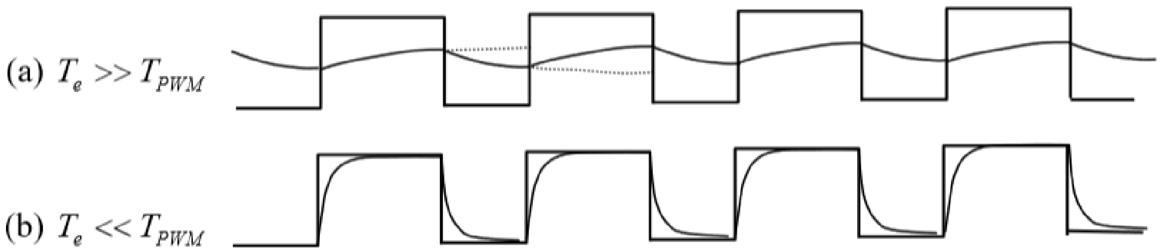

Fig 2.7 Current to the motor is smoothed due to inductance

2.2.2 PWM Switching Characteristics

As the PWM frequency increases, the current driven to the motor becomes smoother, and the nonlinearity due to discrete switching disappears. Furthermore, high PWM frequencies cause no audible noise of switching. The noise disappears as the switching frequency becomes higher than the human audible range, say 15 kHz. Therefore, a higher PWM frequency is in general desirable. However, it causes a few adverse effects. As the PWM frequency increases:

- The heat loss increases and the transistor may over-heat,
- Harmful large voltage spikes and noise are generated, and
- Radio frequency interference and electromagnetic interference become prominent.

The first adverse effect is the most critical one, which limits the capacity of a PWM amplifier. Although no power loss occurs at the switching transistor when it is completely ON or OFF, a significant amount of loss is caused during transition. As the transistor state is switched from OFF to ON or vice versa, the transistor in Figure 2.4 goes through intermediate states, which entail heat loss, as shown in Figure 2.5. Since it takes some finite time for a semiconductor to make a transition, every time it is switched, a certain amount of power is dissipated. As the PWM frequency increases, more power loss and, more importantly, more heat generation occur. Figure 2.8 illustrates the turn-on and turn-off transitions of a switching transistor. When turned on, the collector current *Ic* increases and the voltage *Vce* decreases. The product of these two values provides the switching power loss as shown by broken lines in the figure. Note that turn-off takes a longer time, hence it causes more heat loss.

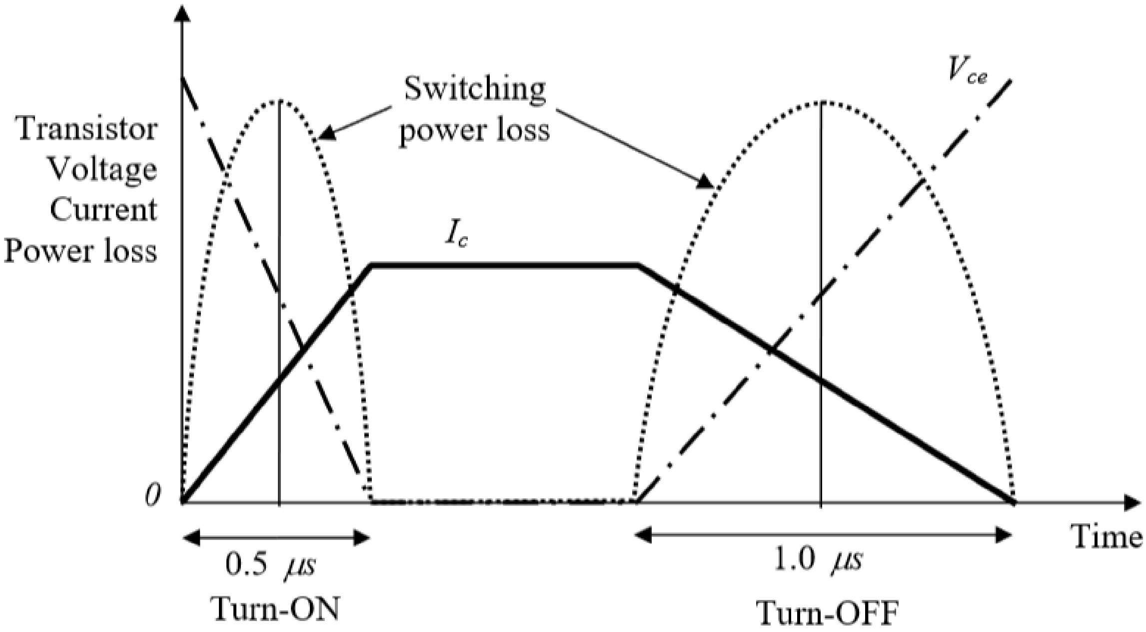

Fig 2.8 Transient responses of transistor current and voltage and associated power loss during turn-on and turn-off state transitions

From Figure 2.8, it is clear that a switching transistor having fast turn-on and turn-off characteristics is desirable, since it causes less power loss and heat generation. Power MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) have very fast switching characteristics, enabling 15 ~ 100 kHz of switching frequencies. For relatively small motors, MOSFETs are widely used in industry due to their fast switching characteristics. For larger motors, IGBTs (Insulated Gate Bipolar Transistor) are the rational choice because of their larger capacity and relatively fast response. As the switching speed increases, the heat loss becomes smaller. However, fast switching causes other problems. Consider eq.(4) again, the dynamic equation of the armature:

$$U = R \,.\, i + L\frac{di}{dt} + E \qquad eq\ 4$$

High speed switching means that the time derivative of current i is large. This generates a large inductance-induced kickback voltage $L\frac{di}{dt}$ that often damages switching semiconductors. As illustrated in Figure 2.9-(a), a large spike is induced when turning on the semiconductor. To get rid of this problem a free-wheeling-diode (FWD) is inserted across the motor armature, as shown in Figure 2.9-(b). As the voltage across the armature exceeds a threshold level, FWD kicks in to bypass the current so that the voltage may be clamped, as shown in figure (c).

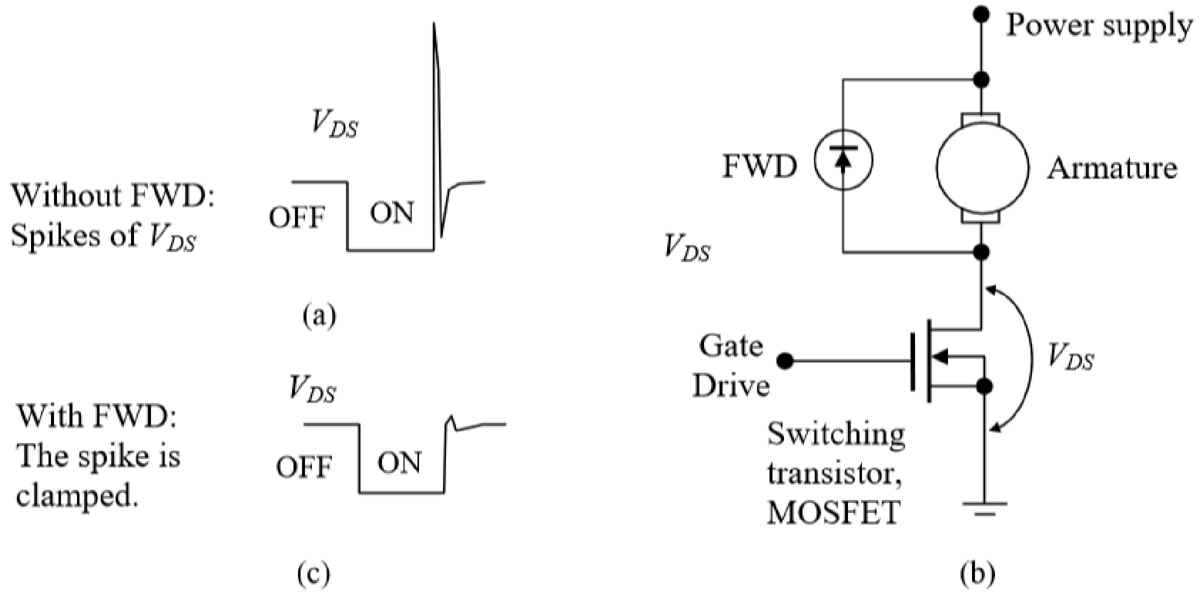

Fig 2.9 Voltage spike induced by inductance (a), free-wheeling diode (b), and the clamped spike with FWD (c)

High speed PWM switching also generates ***Electromagnetic Interference (EMI),*** particularly when the wires between the PWM amplifier and the motor get longer. Furthermore, high speed PWM switching may incur ***Radio-Frequency Interference (RFI).*** Since the PWM waveforms are square, significant RFI can be generated. Whenever PWM switching edges are faster than $10\mu s$, RFI is induced to some extent. An effective method for reducing EMI and RFI is to put the PWM amplifier inside the motor body. This motor architecture, called Integrated Motor or Smart Motor, allows confining EMI and RFI within the motor body by minimizing the wire length between the motor armature and the power transistors.

2.2.3 The H-Bridge and Bipolar PWM Amplifiers

In most robotics applications, bi-directional control of motor speed is necessary. This requires a PWM amplifier to be bipolar, allowing for both forward and backward rotations. The architecture described in the previous section needs to be extended to meet this bipolar requirement. The H-Bridge architecture is commonly used for bipolar PWM amplifiers. As shown in Figure 2.10, the H-Bridge architecture resembles the letter H in the arrangement of switching transistors around the motor armature. Switching transistors A and B are pulled up to the supply voltage V, whereas transistors C and D are connected to ground. Combinations of these four switching transistors provide a variety of operations. In figure (i), gates A and D are ON, and B and C are OFF. This gate combination delivers a current to the armature in the forward direction. When the gate states are reversed, as shown in figure (ii), the direction of current is reversed. Furthermore, the motor coasts off when all the gates are turned OFF, since the armature is totally isolated or disconnected as shown in figure (iii). On the other hand, the armature windings are shortened, when both gates C and D are turned ON and A and B are turned OFF. See figure (iv). This shortened circuit provides a "braking" effect, when the motor rotor is rotating.

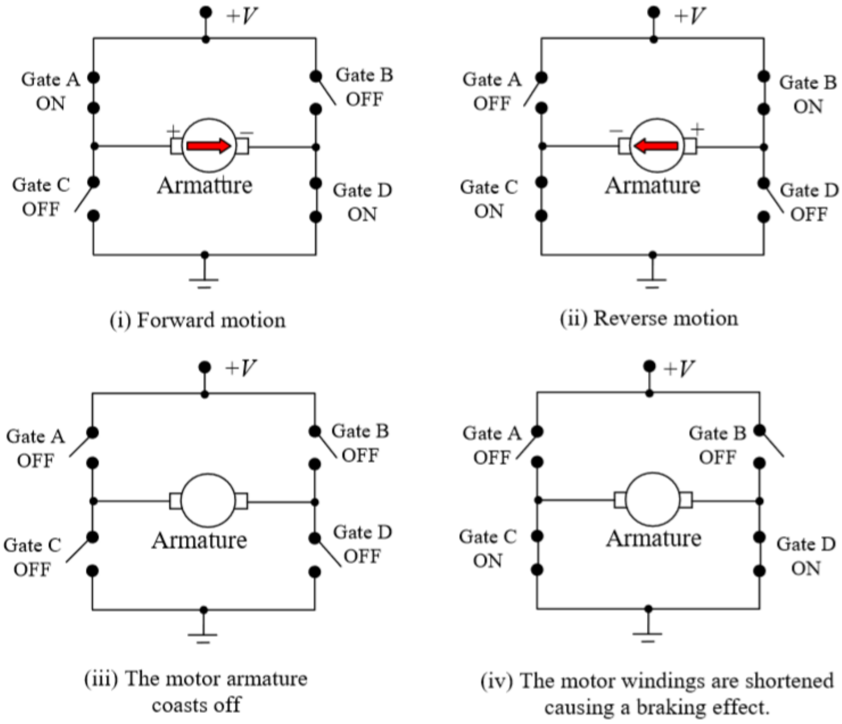

Fig 2.10 H-bridge and four quadrant control

It should be noted that there is a fundamental danger in the H-bridge circuit. A direct short circuit can occur if the top and bottom switches connected to the same armature terminal are turned on at the same time. A catastrophic failure results when one of the switching transistors on the same vertical line in Figure 2.10 fails to turn off before the other turns on. Most of H-bridge power stages commercially available have several protection mechanisms to prevent the direct short circuit.