Dr. Norbert Cheung's Series
in
Electrical Engineering

Level 5 Topic no: 22

Electric Propulsion

Contents

Reference:

C.C. Chan and K.T. Chau, Modern Electric Vehicle Technology, London: Oxford, University Press, 2001

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1. EV Considerations

The choice of electric propulsion systems for EVs mainly depends on three factors—driver expectation, vehicle constraint and energy source. The driver expectation is defined by a driving profile which includes the acceleration, maximum speed, climbing capability, braking and range. The vehicle constraint depends on the vehicle type, vehicle weight and payload. The energy source relates with batteries, fuel cells, capacitors, flywheels and various hybrid sources.

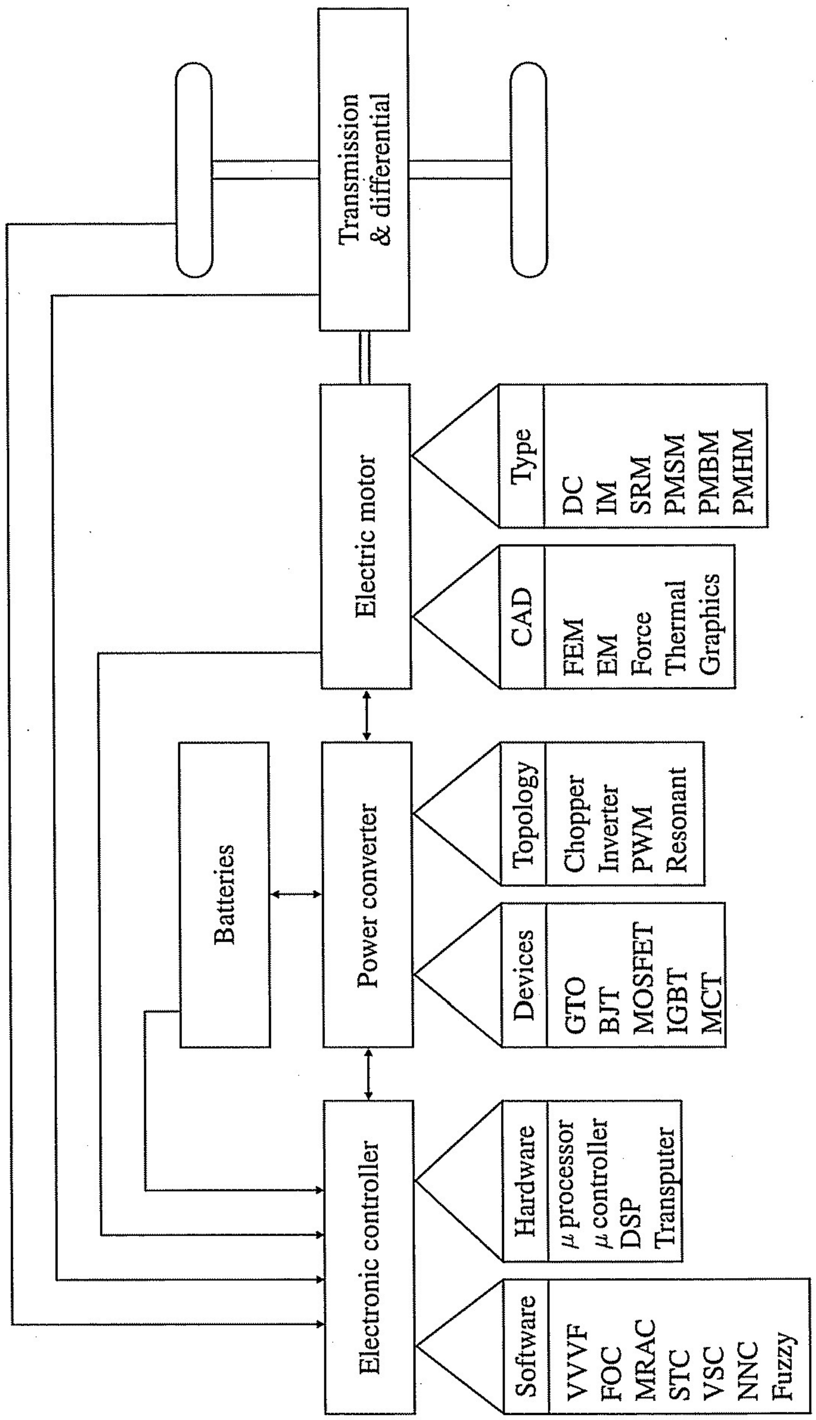


Fig. 5.1. Functional block diagram of an EV propulsion system.

2. Concept of EV Motors

Special Considerations for EV Motors

- EV motors need to offer the maximum torque that is four to five times of the rated torque for temporary acceleration and hill-climbing, while industrial motors generally offer the maximum torque that is twice of the rated torque for overload operation.
- EV motors need to achieve four to five times the base speed for highway cruising, while industrial motors generally achieve up to twice the base speed for constant-power operation.
- EV motors should be designed according to the vehicle driving profiles and drivers' habits, while industrial motors are usually based on a typical working mode.
- EV motors demand both high power density and good efficiency map (high efficiency over wide speed and torque ranges) for the reduction of total vehicle weight and the extension of driving range, while industrial motors generally need a compromise among power density, efficiency and cost with the efficiency optimized at a rated operating point.
- EV motors desire high controllability, high steady-state accuracy and good dynamic performance for multiple-motor coordination, while only special-purpose industrial motors desire such performance.
- EV motors need to be installed in mobile vehicles with harsh operating conditions such as high temperature, bad weather and frequent vibration, while industrial motors are generally located in fixed places.

Key Issues on System Technology

1. Single or Multiple Motor Technology

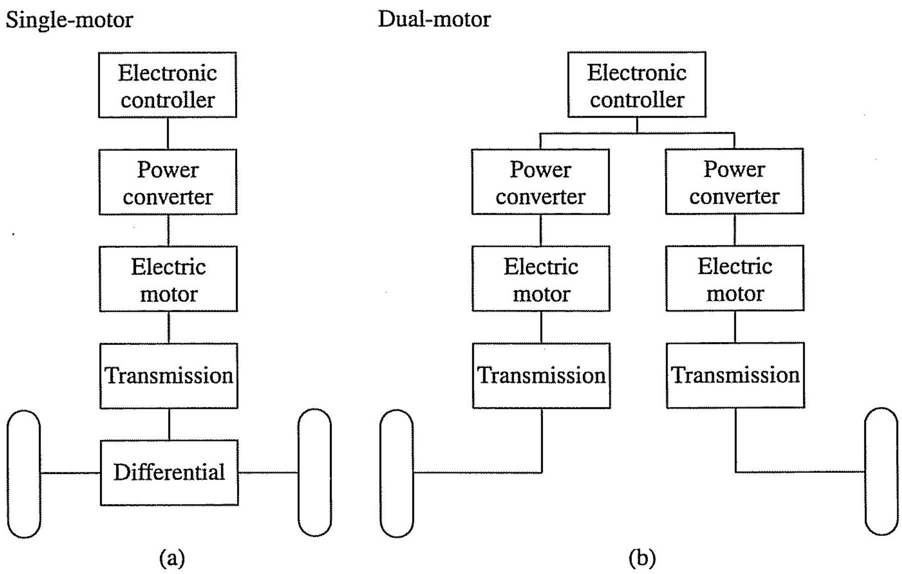


Fig. 5.2. Single- and multiple-motor configurations.

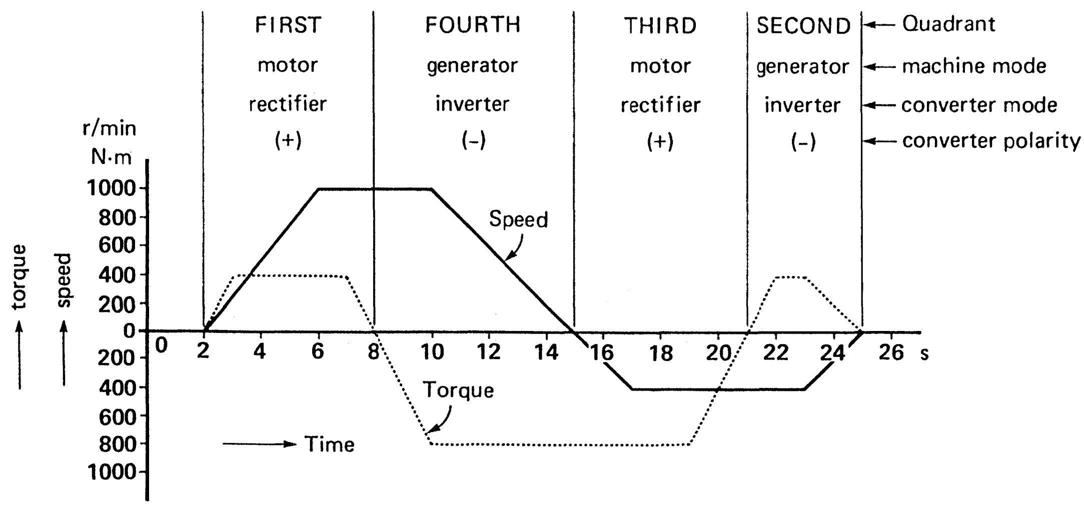
Table 5.1 Comparison of single- and dual-motor configurations

	Single-motor	Dual-motor
Cost	Lower	Higher
Size	Lumped	Distributed
Weight	Lumped	Distributed
Efficiency	Lower	Higher
Differential	Mechanical	Electronic

2. Fixed or Multiple Gear Transmission

Table 5.2 Comparison of fixed- and variable-gearing transmissions

	Fixed-gearing	Variable-gearing
Motor rating	Higher	Lower
Inverter rating	Higher	Lower
Cost	Lower	Higher
Size	Smaller	Larger
Weight	Lower	Higher
Efficiency	Higher	Lower
Reliability	Higher	Lower



3. Gear or Gearless (Direct-Drive)

Geared or gearless—the use of fixed-speed gearing with a high gear ratio allows EV motors to be designed for high-speed operation, resulting high power density. The maximum speed is limited by the friction and windage losses as well as transaxle tolerance. On the other hand, EV motors can directly drive the transmission axles or adopt the in-wheel drive without using any gearing (gearless operation). However, it results the use of low-speed outer-rotor motors which generally suffer from relatively low power density.

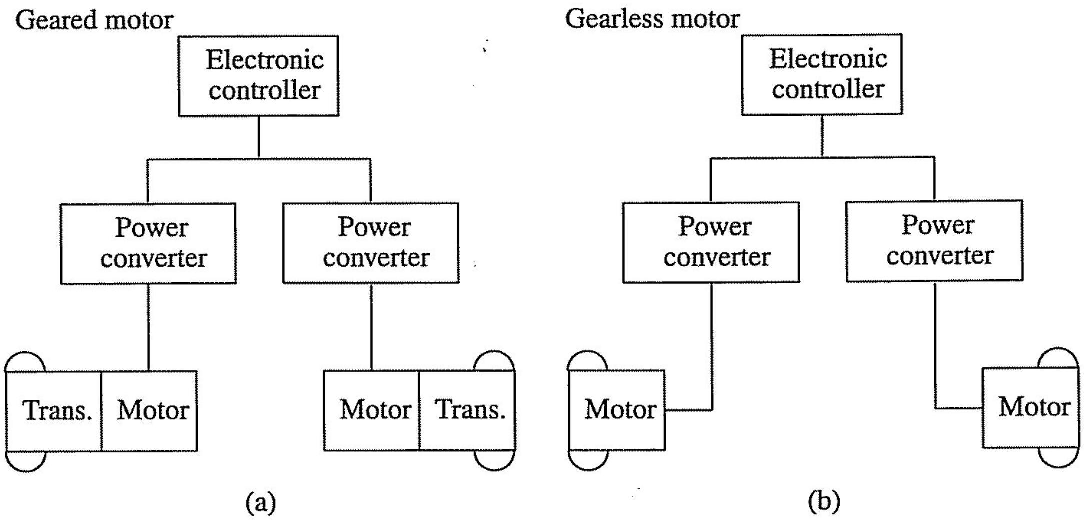


Fig. 5.3. In-wheel motor configurations.

4. System Voltage

cater for different EVs. Roughly, the system voltage is governed by the battery weight which is about 30% of the total vehicle weight. In practice, higher power motors adopt higher voltage levels. For examples, the GM EV1 adopts the 312-V voltage level for its 102-kW motor, whereas the Reva EV adopts the 48-V voltage level for its 13-kW motor.

5. Integration

Integration—the integration of the motor with the converter, controller, transmission and energy source is prime important consideration. The EV motor designer should fully understand the characters of these components, thus to design the motor under this given environment. It is quite different with the normal standard motors under standard power source for normal industrial drives.

2. Classification of EV Motors

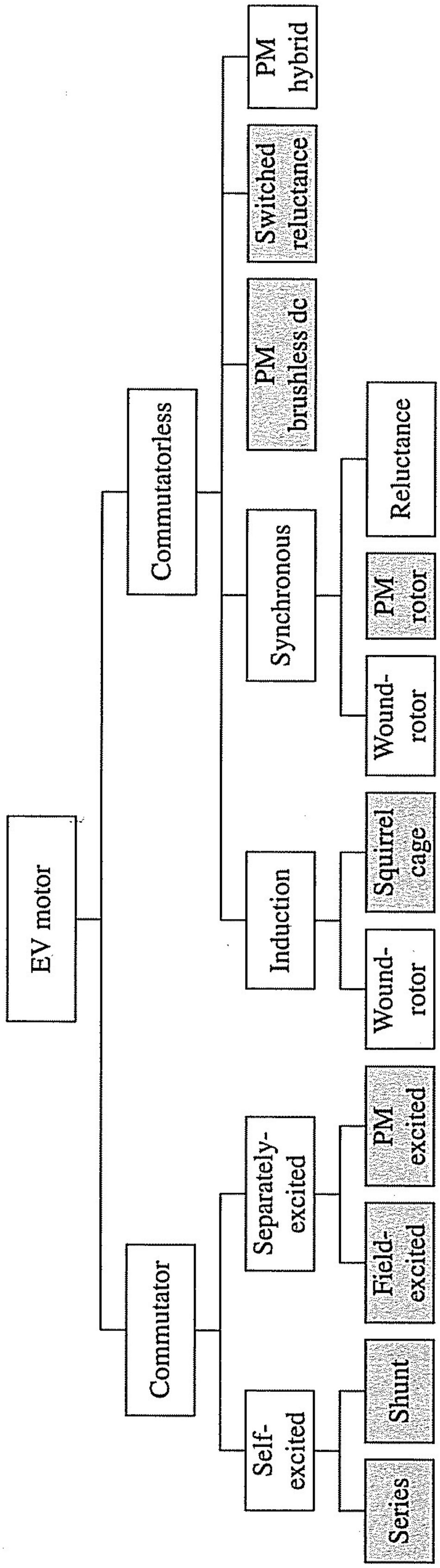


Fig. 5.4. Classification of EV motors.

The Brush type DC motor

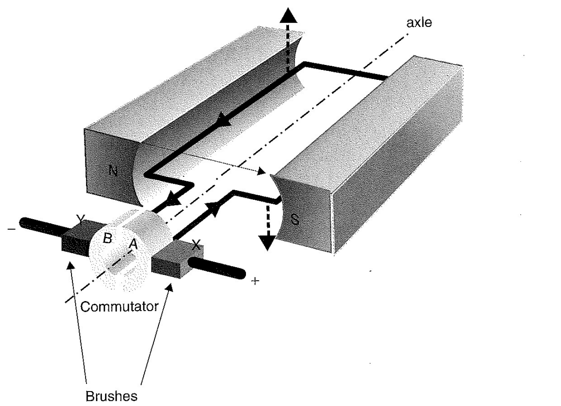


Diagram to explain the operation of the simple permanent magnet DC motor

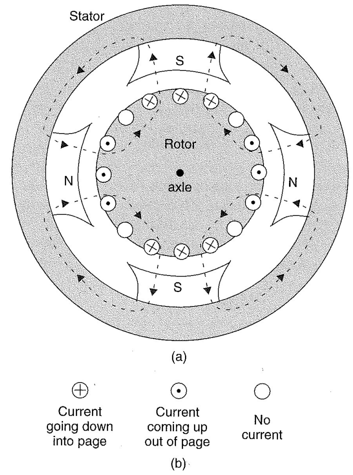


Figure 6.2 (a) Cross-section through a four-pole DC motor. The dotted lines shows the magnetic flux. The motor torque is clockwise. (b) shows the convention used to indicate the direction of current flow in wires drawn in cross-section

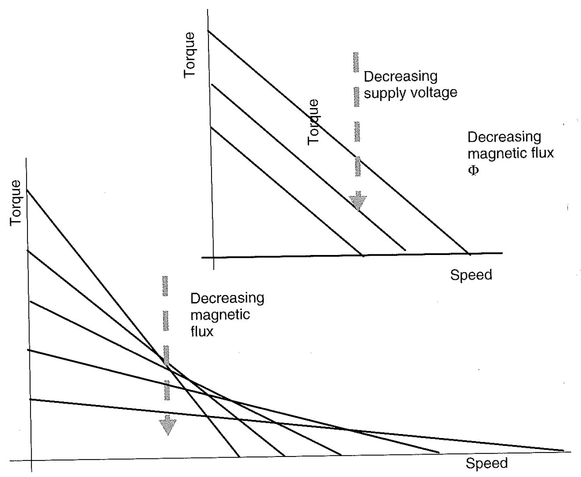


Figure 6.5 How changing the supply voltage and the magnetic field strength affects the torque speed characteristic of the DC motor

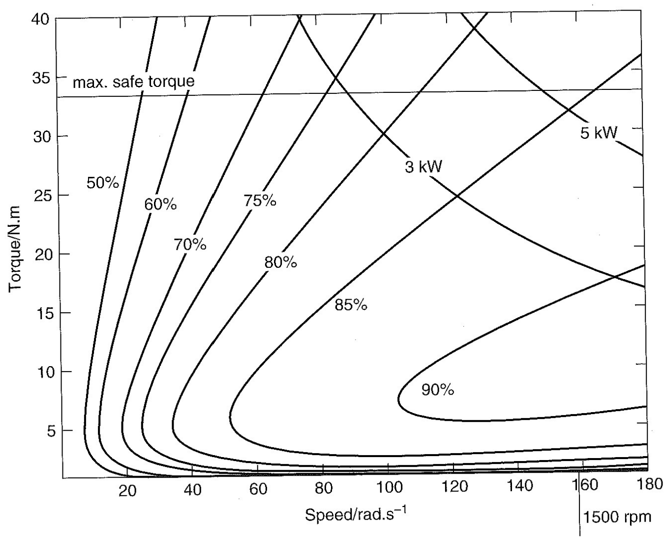


Figure 6.7 Efficiency map for a typical permanent magnet DC motor, with brushes

The Brushless DC motor

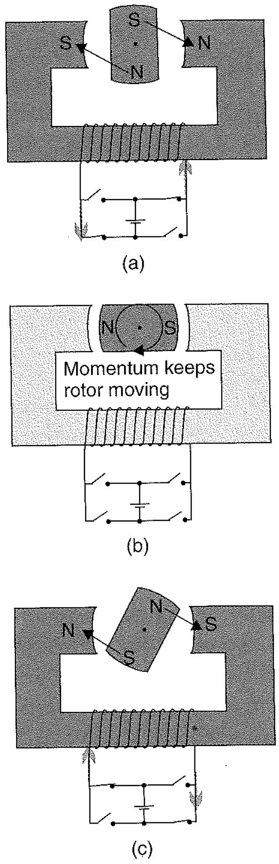


Figure 6.24 Diagram showing the basis of operation of the brushless DC motor

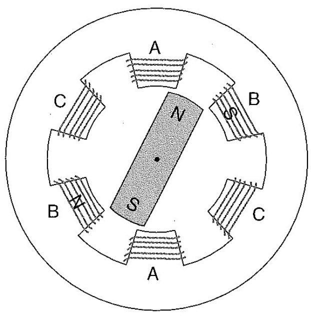


Diagram showing an arrangement of three coils on the stator of a BLDC motor

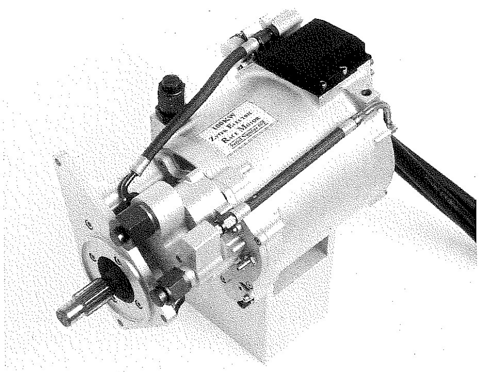
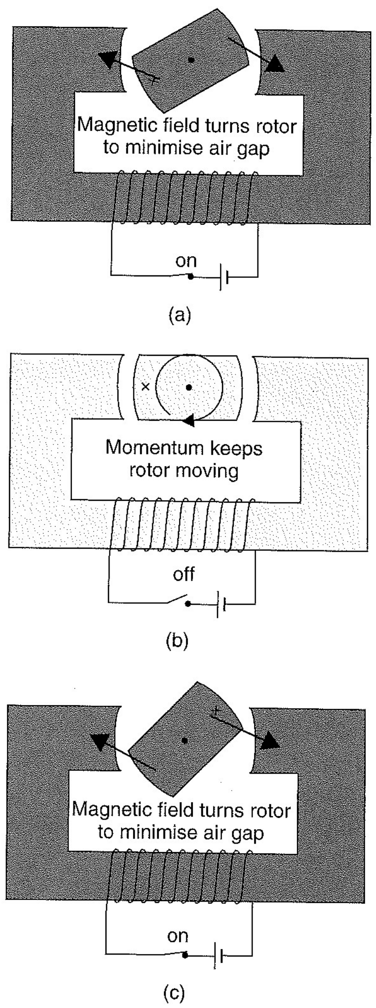


Figure 6.26 100 kW, oil cooled BLDC motor for automotive application. This unit weighs just 21 kg (photograph reproduced by kind permission of Zytek Ltd.)

The Switched Reluctance Motor



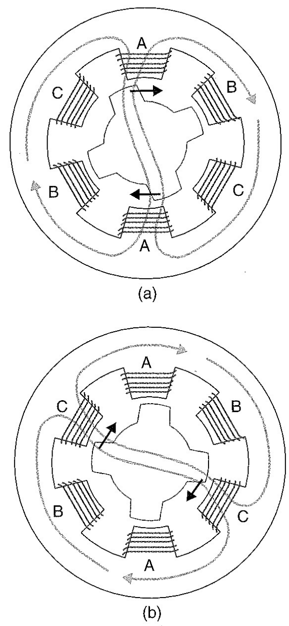


Diagram showing the operation of an SR motor with a four salient pole rotor

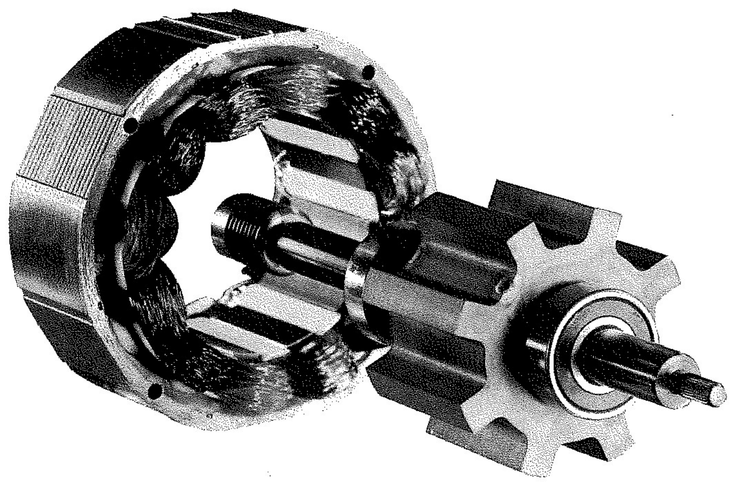


Figure 6.29 The rotor and stator from an SR motor (photograph reproduced by kind permission of SR Drives Ltd.)

The Induction Motor

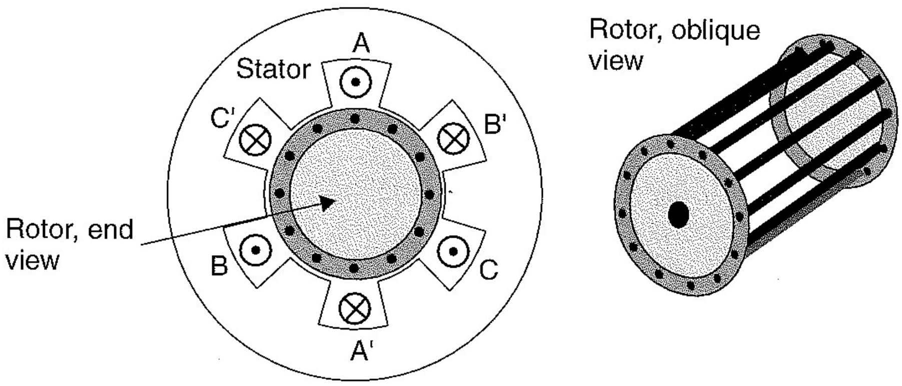


Figure 6.30 Diagram showing the stator and rotor of an induction motor

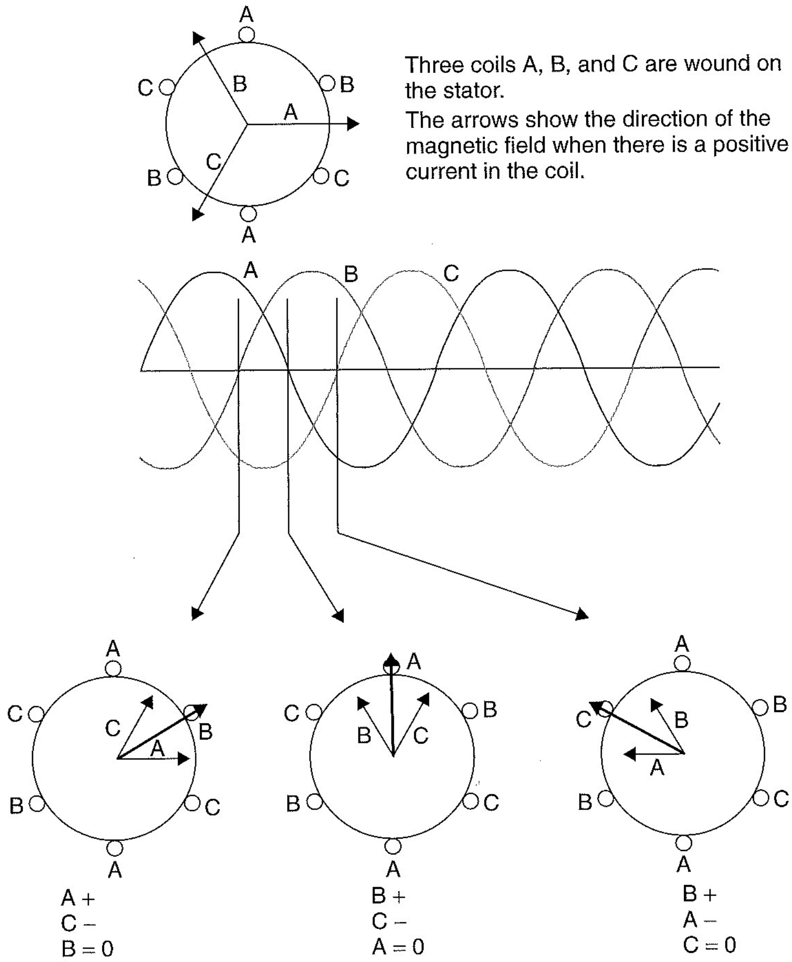


Figure 6.31 Diagrams to show how a rotating magnetic field is produced within an induction motor

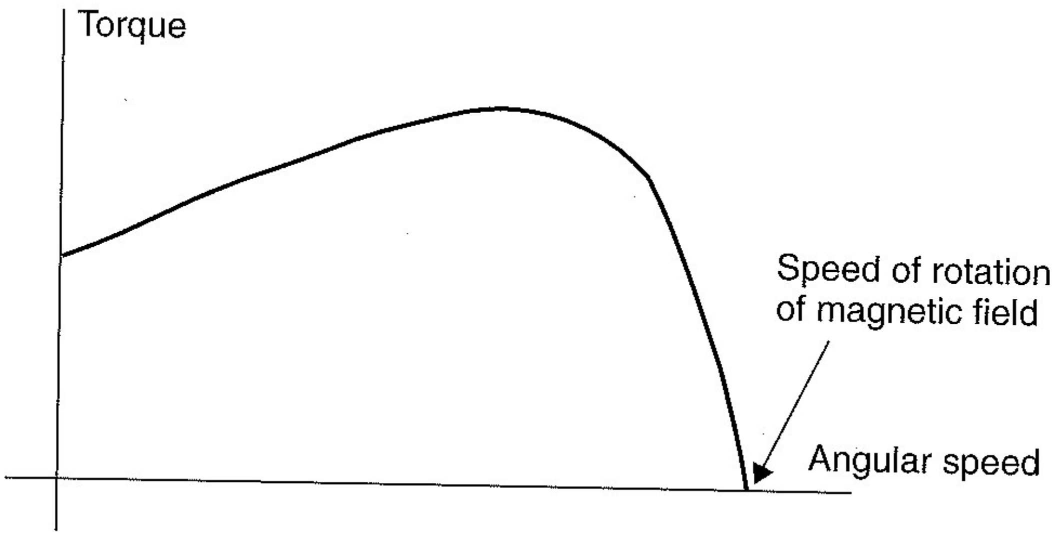


Figure 6.32 Typical torque/speed curve for an induction motor

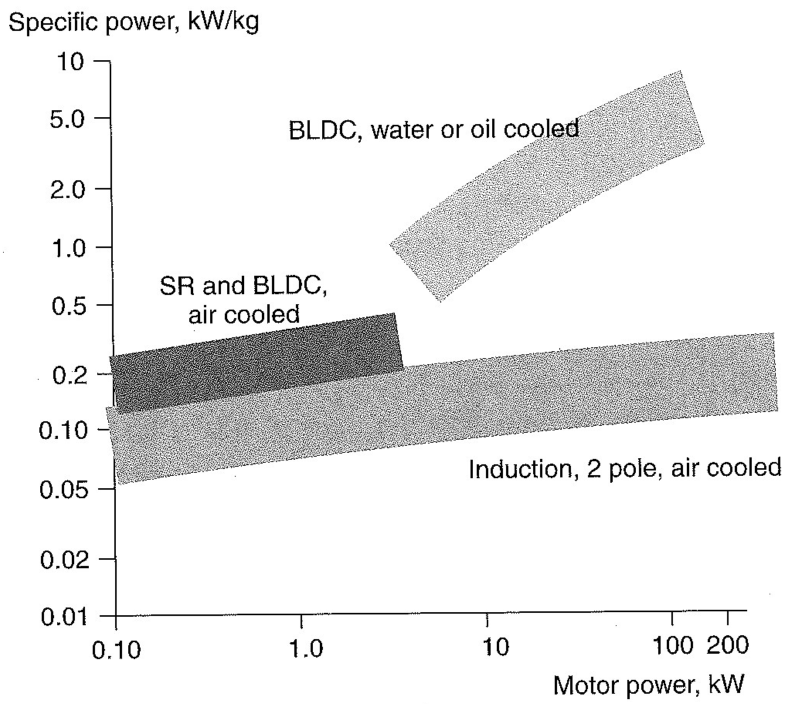


Figure 6.34 Chart to show the specific power of different types of electric motor at different powers. The power here is the continuous power. Peak specific powers will be about 50% higher. Note the logarithmic scales (this chart was made using data from several motor manufacturers.)

Table 5.3 Applications of EV motors

EV models	EV motors
Fiat Panda Elettra	Series dc motor
Mazda Bongo	Shunt dc motor
Conceptor G-Van	Separately excited dc motor
Suzuki Senior Tricycle	PM dc motor
Fiat Seicento Elettra	Induction motor
Ford Th!nk City	Induction motor
GM EV1	Induction motor
Honda EV Plus	PM synchronous motor
Nissan Altra	PM synchronous motor
Toyota RAV4	PM synchronous motor
Chloride Lucas	Switched reluctance motor

The basic consideration of motor design includes magnetic loading—the peak of fundamental component of radial flux density in the air-gap of the motor, electric loading—the total r.m.s. current per unit length of periphery of the motor or ampere-turns per unit periphery, power per unit volume and weight, torque per unit volume and weight, flux density at each part of the magnetic circuit, speed, torque and power, losses and efficiency, and thermal design and cooling.

Table 5.4 Evaluation of EV motors

	Dc motor	Induction motor	PM brushless motor	SR motor	PM hybrid motor
Power density	2.5	3.5	5	3.5	4
Efficiency	2.5	3.5	5	3.5	5
Controllability	5	4	4	3	4
Reliability	3	5	4	5	4
Maturity	5	5	4	4	3
Cost	4	5	3	4	3
Total	22	26	25	23	23

In order to evaluate the aforementioned EV motor types, a point grading system is adopted. The grading system consists of six major characteristics and each of them is graded from 1 to 5 points. As listed in Table 5.4, this evaluation indicates that induction motors are relatively most acceptable. When the cost and maturity of PM brushless (including ac or dc) motors have significant improvements, these motors will be most attractive. Conventional dc motors seem to be losing their competitive edges, whereas both SR and PM hybrid motors have increasing potentials for EV propulsion.

4. EV Power Electronics

A. Switching Devices

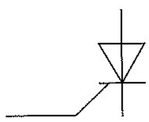
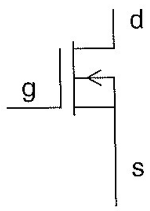
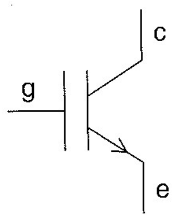
Criteria for power switching device selection

- Ratings—the voltage rating is based on the battery nominal voltage, maximum voltage during charging, and maximum voltage during regenerative braking. On the other hand, the current rating depends on the motor peak power rating and number of power devices connected in parallel. When paralleling these devices, on-state and switching characteristics have to be matched.
- Switching frequency—switching at higher frequencies can bring down the filter size and help to meet the electromagnetic interference (EMI) limitation requirements. Over the switching frequency of 20 kHz, there is no acoustic noise problem.
- Power losses—the on-state conduction drop or loss should be minimum while the switching loss should be as low as possible. Since higher switching frequencies increase the switching loss, switching the device at about 10 kHz seems to be an optimum for efficiency, power density, acoustic noise and EMI considerations. The leakage current should also be less than 1 mA to minimize the off-state loss.
- Base/gate driverability—the device should allow for simple and secure base/gate driving. The corresponding driving signal may be either triggering voltage/current or linear voltage/current. The voltage-mode driving involves very little energy and is generally preferable.
- Dynamic characteristics—the dynamic characteristics of the device should be good enough to allow for high dv/dt capability, high di/dt capability and easy paralleling. The internal anti-parallel diode should have similar dynamic characteristics as the main device.
- Ruggedness—the device should be rugged to withstand a specific amount of avalanche energy during over-voltage and be protected by fast semiconductor fuses during over-current. It should operate with no or minimal use of snubber circuits. Since EVs are frequently accelerated and decelerated, the device is subjected to thermal cycling at frequent intervals. It should reliably work under these conditions of thermal stress.
- Maturity and cost—since the cost of power devices is one of the major parts in the total cost of electric propulsion systems, these devices should be economical. Some recent power devices such as the high-power MCT are not yet mature for EV applications.

Table 5.5 Evaluation of EV power devices

	GTO	BJT	MOSFET	IGBT	MCT
Ratings	5	4	2	5	3
Switching frequency	1	2	4	4	4
Power losses	2	3	4	4	4
Base/gate driveability	2	3	5	5	5
Dynamic characteristics	2	3	5	5	5
Ruggedness	3	3	5	5	5
Maturity	5	5	4	4	2
Cost	4	4	4	4	2
Total	24	27	33	36	30

Table 6.1 Key data for the main types of electronic switch used in modern power electronic equipment

Type	Thyristor	MOSFET	IGBT
symbol			
Max. voltage (V)	4500	1000	1700
Max. current (A)	4000	50	600
Switching time (μs)	10–25	0.3–0.5	1–4

B. Power Converters

Furthermore, four-quadrant dc choppers are employed for reversible and regenerative speed control of dc motors. A four-quadrant dc chopper is shown in Fig. 5.5.

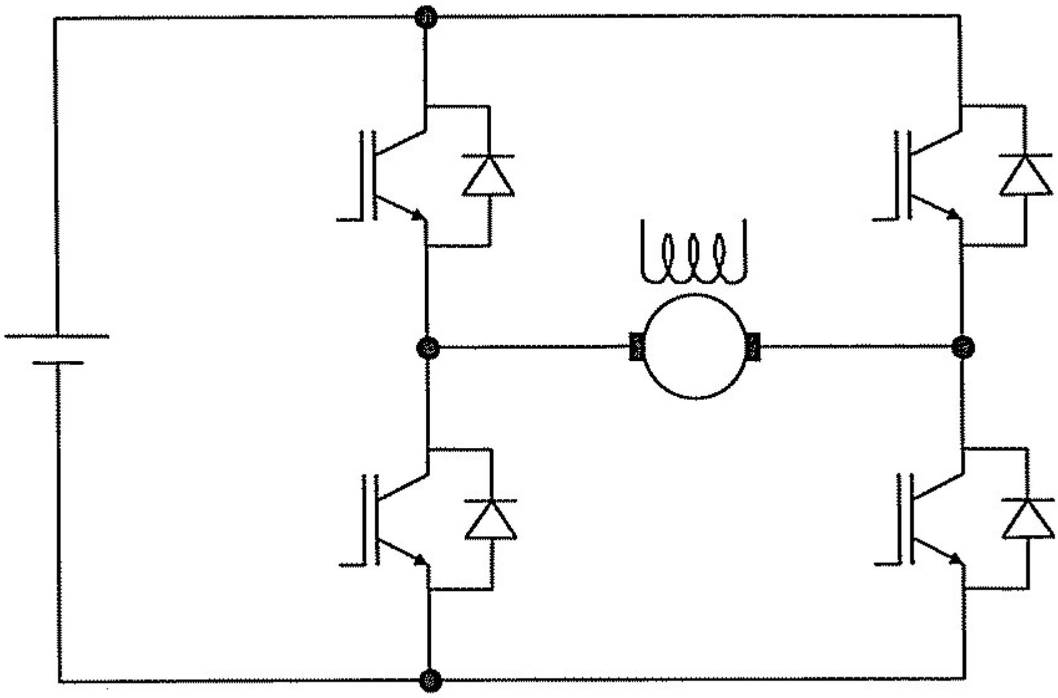


Fig. 5.5. Four-quadrant dc chopper.

Inverters are generally classified into voltage-fed and current-fed types. Because of the need of a large series inductance to emulate a current source, current-fed inverters are seldom used for electric propulsion. In fact, voltage-fed inverters are almost exclusively used because they are very simple and can have power flow in either direction. A typical three-phase full-bridge voltage-fed inverter is shown

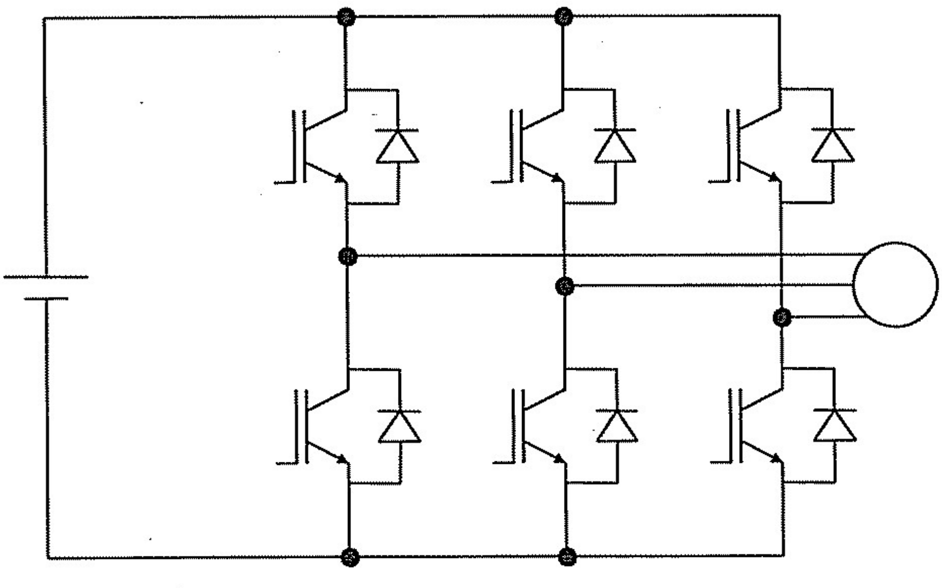


Fig. 5.6. Three-phase full-bridge voltage-fed inverter.

C. Soft Switching

Instead of using hard or stressed switching, power converters can adopt soft or relaxed switching. The key of soft switching is to employ a resonant circuit to shape the current or voltage waveform such that the power device switches at zero-current or zero-voltage condition. In general, the use of soft-switching converters possess the following advantages:

- Due to zero-current or zero-voltage switching condition, the device switching loss is practically zero, thus giving high efficiency.
- Because of low heat sinking requirement and snubberless operation, the converter size and weight are reduced, thus giving high power density.
- The device reliability is improved because of minimum switching stress during soft switching.
- The EMI problem is less severe and the machine insulation is less stressed because of lower *dv/dt* resonant voltage pulses.
- The acoustic noise is very small because of high frequency operation.

Table 5.6 Comparison of hard switching and soft switching for EV converters

	Hard switching	Soft switching
Switching loss	Severe	Almost zero
Overall efficiency	Norm	Possibly higher
Heat-sinking requirement	Norm	Possibly lower
Hardware count	Norm	More
Overall power density	Norm	Possibly higher
EMI problem	Severe	Low
Dv/dt problem	Severe	Low
Modulation scheme	Versatile	Limited
Maturity	Mature	Developing
Cost	Norm	Higher

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