Dr. Norbert Cheung's Series in Electrical Engineering

Level 5 Topic no: 23

Electric Motors for EV

Contents

Reference:

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

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1. DC Motor Drives

Dc motor drives are classified as wound-field and PM dc types. The former has the field winding and the field can be controlled by the dc current, whereas the latter has no field winding and the PM field is uncontrollable. Various dc motor drives have ever been widely applied to different EVs because of their technological maturity and control simplicity.

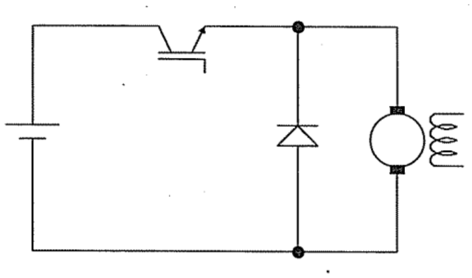
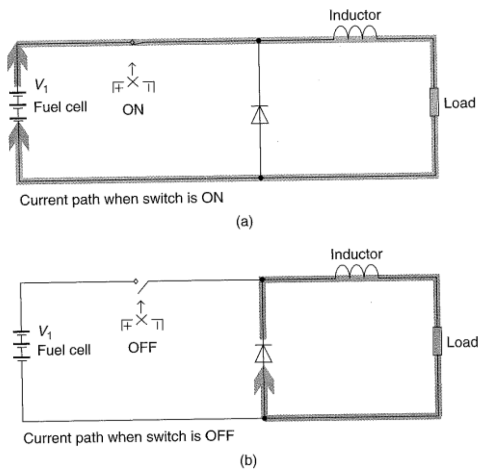


Fig. 5.9. Basic one-quadrant dc chopper control.



$$V_2 = \frac{t_{ON}}{t_{ON} + t_{OFF}} V_1$$

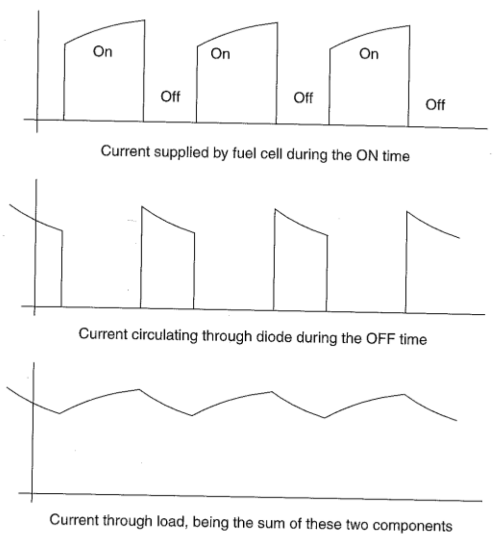


Figure 6.13 Currents in the step down switch mode regulator circuit

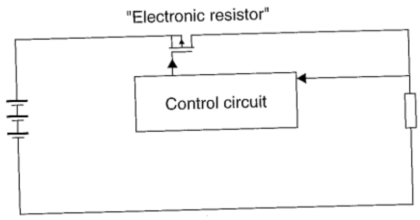
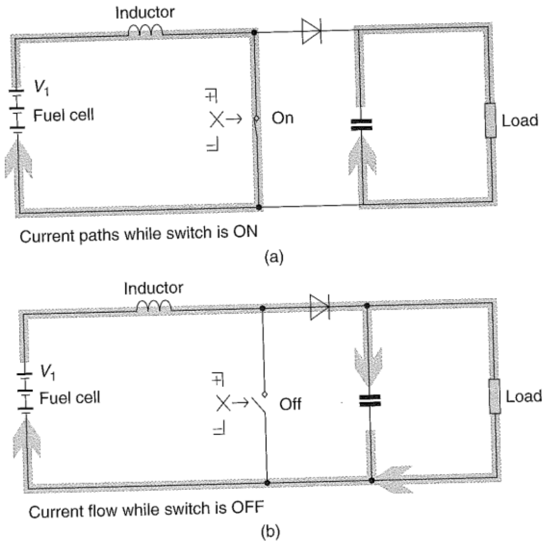


Figure 6.14 Linear regulator circuit



$$V_2 = \frac{t_{ON} + t_{OFF}}{t_{OFF}} V_1$$

Step up mode

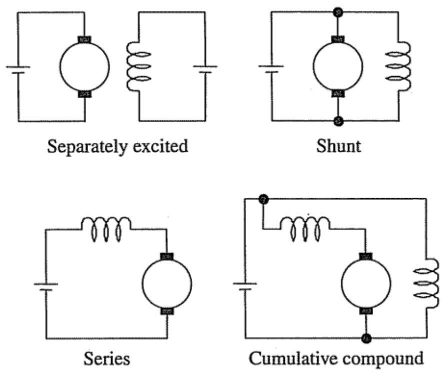


Fig. 5.10. Wound-field dc motors.

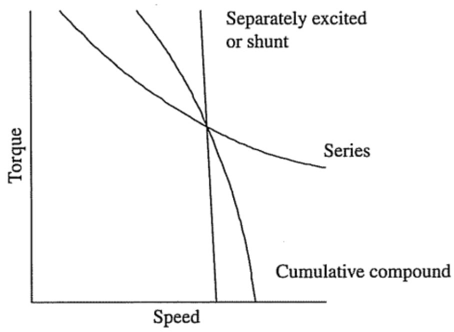


Fig. 5.11. Torque-speed characteristics of wound-field dc motors.

Both wound-field and PM dc motors suffer from the same problem due to the use of commutators and brushes. Commutators cause torque ripples and limit the motor speed, while brushes are responsible for friction and radio-frequency interference (RFI). Moreover, due to the wear and tear, periodic maintenance of commutators and brushes is always required. These drawbacks make them less reliable and unsuitable for maintenance-free operation, and limit them to be widely applied for modern EV propulsion.

As mentioned before, the major advantages of dc motors are their maturity and simplicity. The simplicity is mainly due to their simple control because the air-gap flux Φ and the armature current I_a, hence the motor speed ω_m and torque T, can be independently controlled. No matter wound-field or PM dc motors, they are governed by the following basic equations:

$$E = K_e \Phi \omega_m$$
$$V_a = E + R_a I_a$$
$$T = K_e \Phi I_a,$$

where E is the back emf, V_a is the armature voltage, R_a is the armature resistance, and K_e is named as the back emf constant or torque constant. For those wound-field dc motors, Φ is linearly related to the field current I_f which may be independently controlled, dependent on I_a, dependent on V_a, or dependent on both I_a and V_a, respectively for those separately excited, series, shunt, or cumulative compound types. In contrast, Φ is essentially uncontrollable for those PM dc motors.

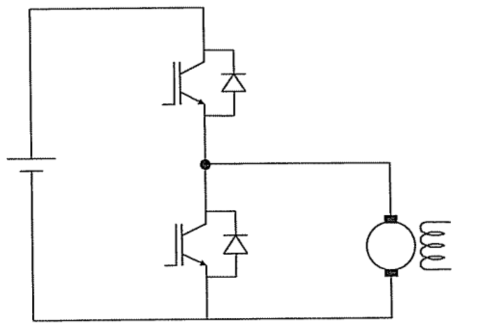


Fig. 5.12. Two-quadrant dc choppers for EV propulsion.

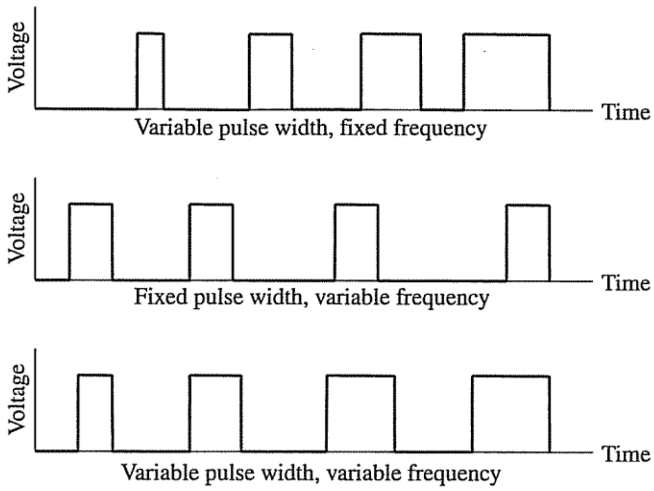


Fig. 5.13. Dc chopper controlled output voltages.

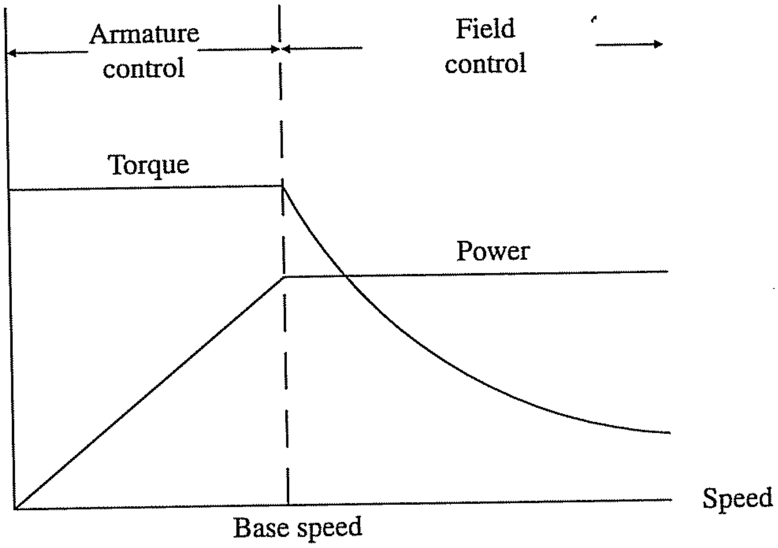


Fig. 5.19. Combined armature and field control of dc motor drive.

2. AC drives

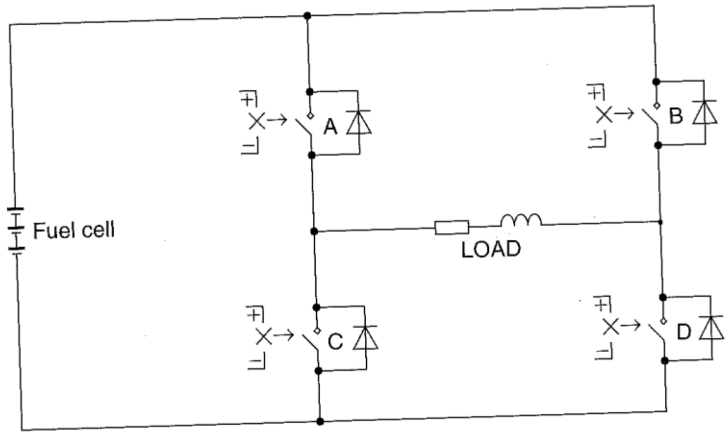


Figure 6.17 H-bridge inverter circuit for producing single phase alternating current

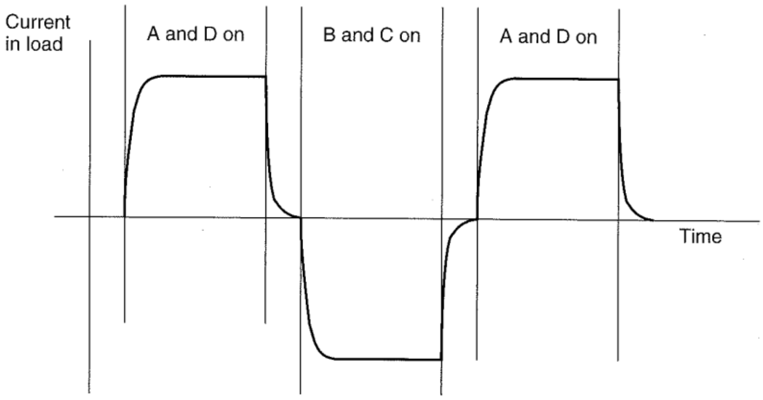


Figure 6.18 Current/time graph for a square wave switched single-phase inverter

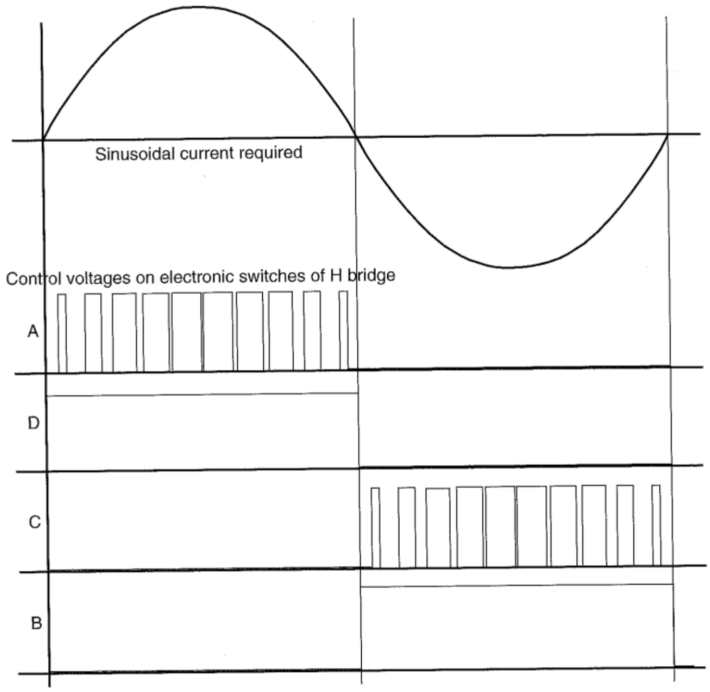


Figure 6.19 Pulse width modulation switching sequence for producing an approximately sinusoidal alternating current from the circuit of Figure 6.17

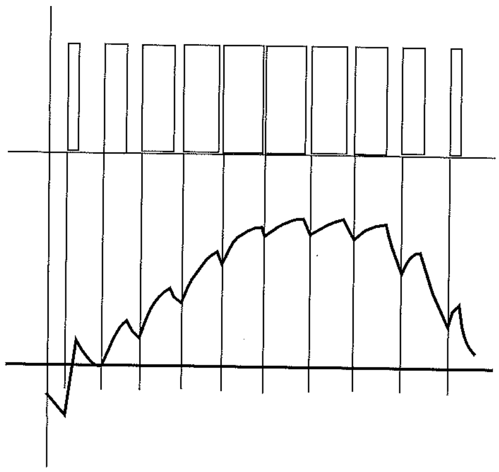


Figure 6.20 Typical voltage/time graph for a pulse modulated inverter

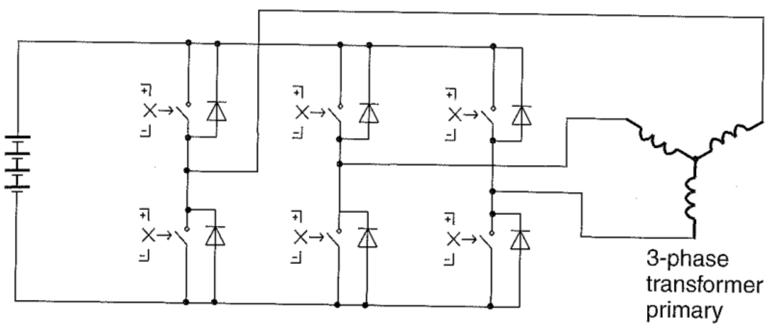


Figure 6.21 Three-phase inverter circuit

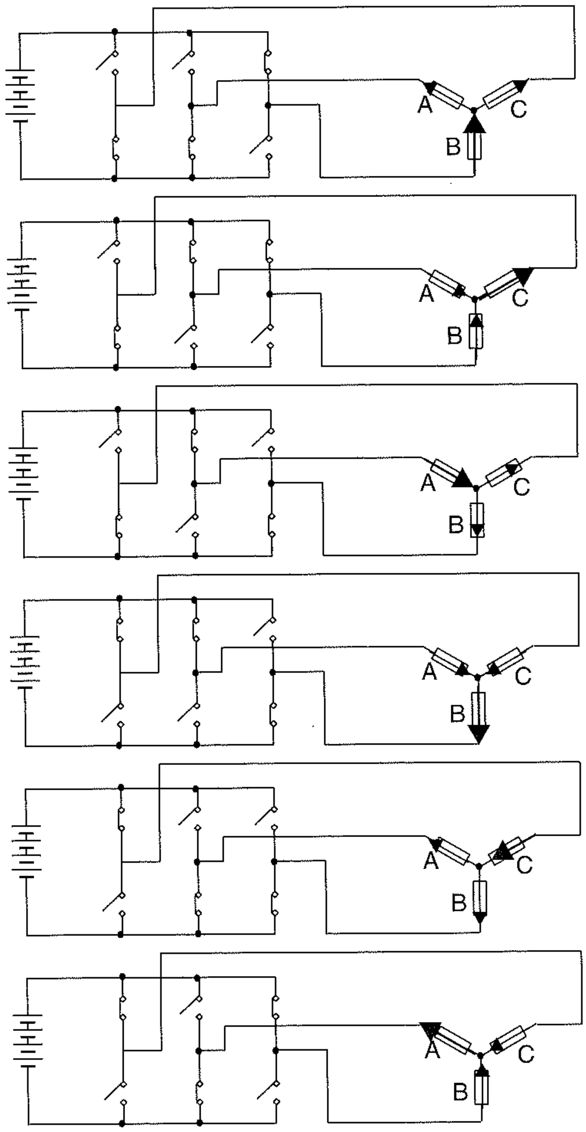


Figure 6.22 Switching pattern to generate three-phase alternating current

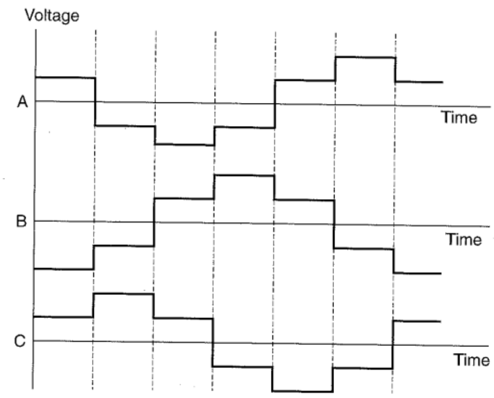


Figure 6.23 Current/time graphs for the simple three-phase AC generation system shown in Figure 6.22, assuming a resistive load. One complete cycle for each phase is shown. Current flowing *out* from the common point is taken as *positive*

3. The Induction Motor Drives

induction motor drives is the most mature technology among various commutatorless motor drives. There are two types of induction motors, namely wound-rotor and squirrel-cage. Because of high cost, need of maintenance and lack of sturdiness, wound-rotor induction motors are less attractive than squirrel-cage counterparts, especially for electric propulsion in EVs.

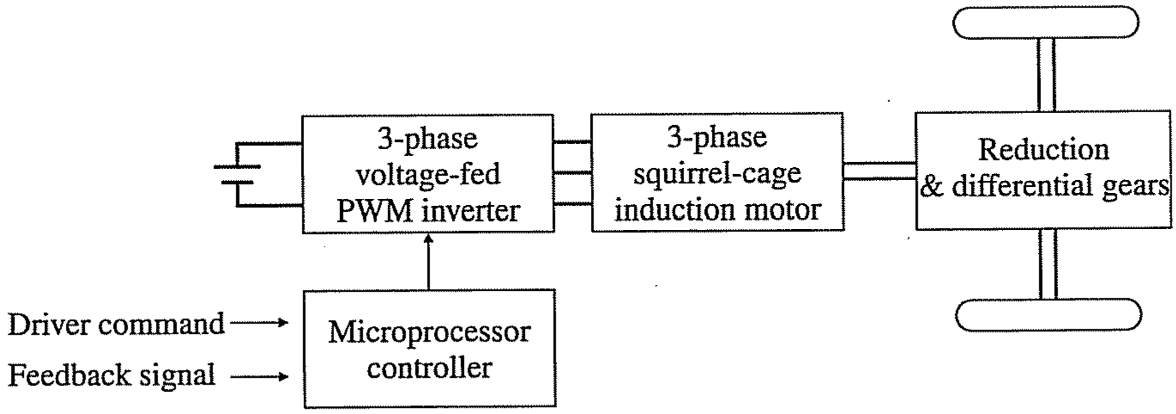


Fig. 5.21. Basic EV induction motor drive configuration.

There are numerous PWM schemes that have been available, such as the sinusoidal PWM, uniform PWM, optimal PWM, delta PWM, random PWM, equal-area PWM, hysteresis-band PWM, and space vector PWM. Both the current-controlled hysteresis-band PWM and space vector PWM have been widely used for induction motor drives in EVs. Nevertheless, the voltage-controlled equal-area

PWM scheme is particularly designed for battery-powered induction motor drives in EVs (Chan and Chau, 1991).

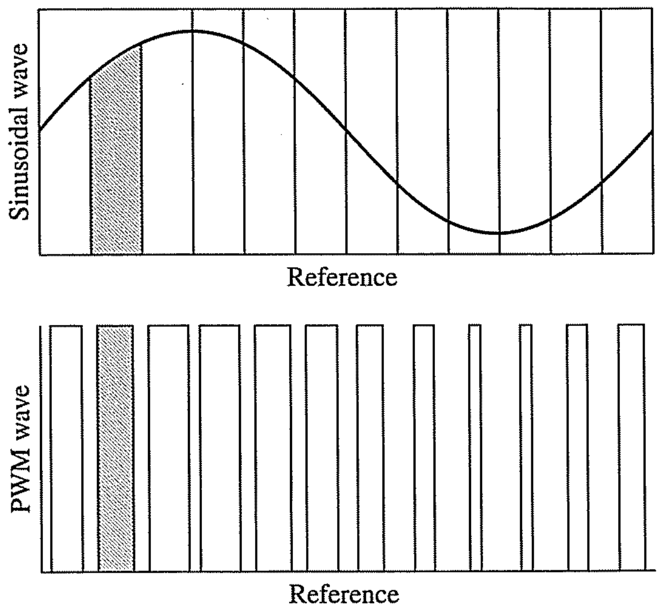


Fig. 5.23. Equal-area PWM.

There are three state-of-the-art control strategies, namely variable-voltage variable-frequency (VVVF) control, field-oriented control (FOC) which is also called as vector control or decoupling control, and pole-changing control. The basic equation of induction motor speed control is governed by:

$$N = N_s(1 - s) = \frac{60f}{p}(1 - s),$$

where N is the motor speed, N_s is the rotating-field synchronous speed, s is the slip, p is the number of pole pairs, and f is the supply frequency. Thus, the motor speed can be controlled by variations in f, p and/or s

VVVF Control

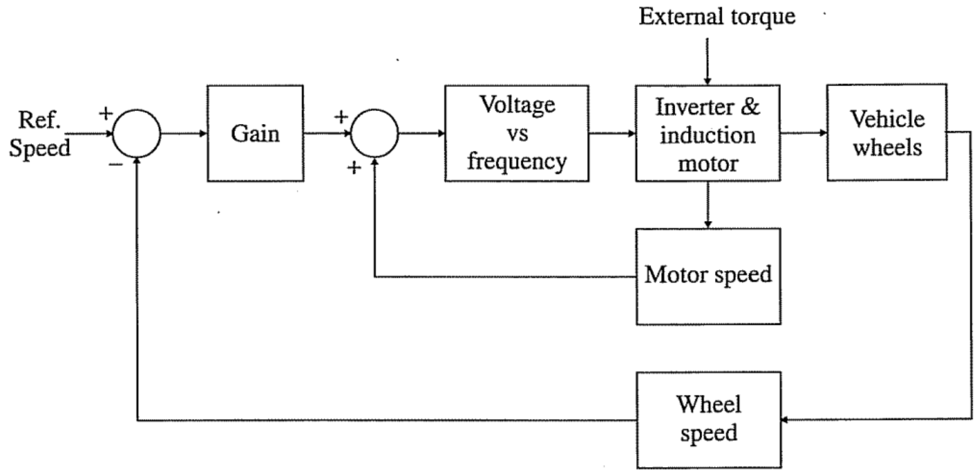


Fig. 5.28. VVVF control of induction motor drives.

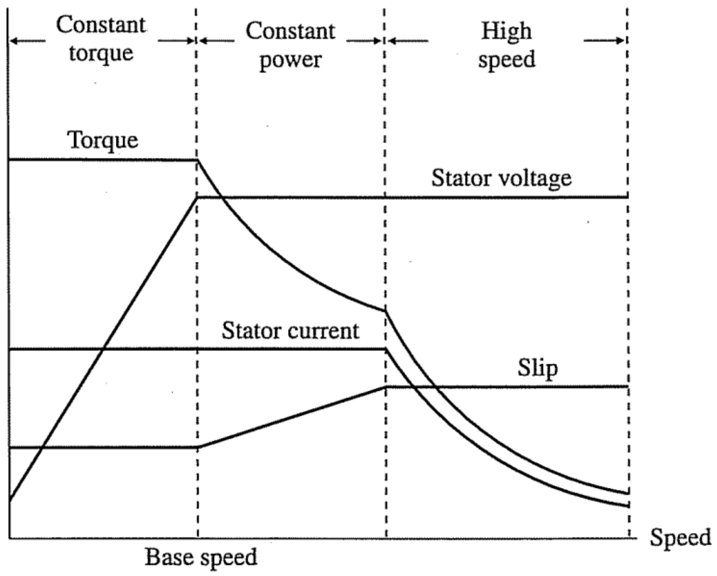


Fig. 5.29. Characteristics of induction motor drives.

FOC Control

In order to improve the dynamic performance of induction motor drives for EV propulsion, FOC is preferred to VVVF control. By using FOC, the mathematical model of induction motors is transformed from the stationary reference frame (*d–q* frame) to the general synchronously rotating frame (*x–y* frame)

Therefore, by means of this FOC, the motor torque can be effectively controlled by adjusting the torque component as long as the field component remains constant. Hence, induction motor drives can offer the desired fast transient response similar to that of separately excited dc motor drives. The corresponding block diagram of induction motor drives using FOC is shown in the Fig. 5.32.

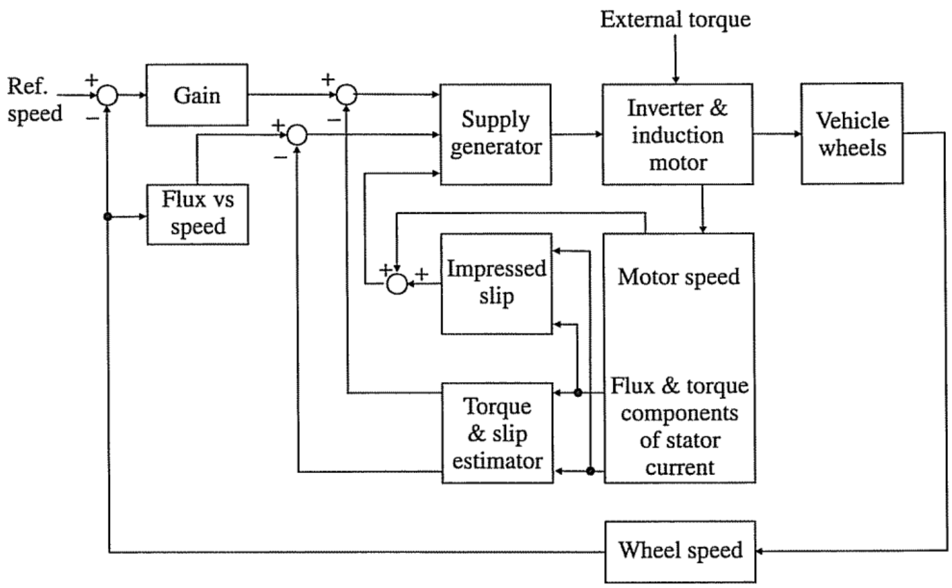


Fig. 5.32. FOC of induction motor drives.

Pole Changing Control

It is well known that a change of the number of pole pairs of induction motor drives can adjust the rotating-field synchronous speed.

Its basic principle can be illustrated by Fig. 5.37. Each stator winding consists of two coil groups, and the change in the current direction in these coil groups causes the change of pole numbers. Figure 5.38 shows a newly proposed dual-inverter six-phase pole-changing EV induction motor drive that can offer both 4-pole and 8-pole operations (Chau *et al.*, 2000). The corresponding maximum torque characteristics are shown in Fig. 5.39. Hence, the high-speed constant-power capability can be remarkably extended, which is particularly desirable for EV cruising.

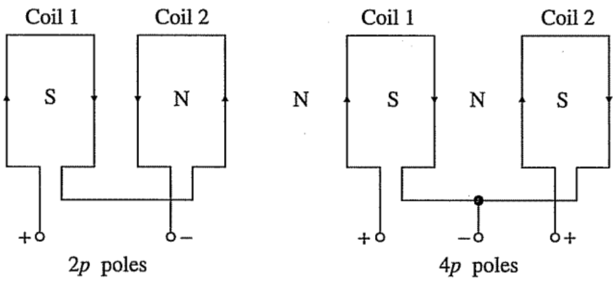


Fig. 5.37. Principle of pole-changing control.

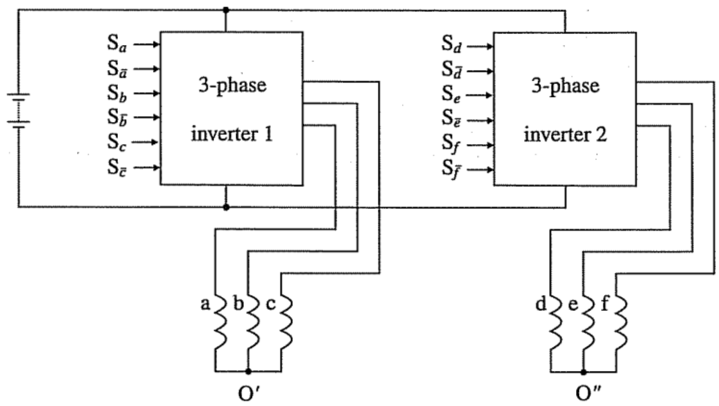


Fig. 5.38. Dual-inverter pole-changing control of an EV induction motor drive.

4. Permanent Magnet Motors

The classification of PM motor drives is diverse. By considering the waveform feeding into the motor terminals, they can be classified as:

- PM dc motor drives and
- PM ac motor drives.

Among those modern motor drives, PM brushless motor drives are most capable of competing with induction motor drives for electric propulsion. Their advantages are summarized below:

- Since the magnetic field is excited by high-energy PMs, the overall weight and volume can be significantly reduced for a given output power, leading to higher power density.
- Because of the absence of rotor copper losses, their efficiency is inherently higher than that of induction motors.
- Since the heat mainly arises in the stator, it can be more efficiently dissipated to surroundings.
- Since PM excitation suffers from no risk of manufacturing defects, overheating or mechanical damage, their reliability is inherently higher.
- Because of lower electromechanical time constant of the rotor, the rotor acceleration at a given input power can be increased.

The system configuration of PM brushless motor drives for electric propulsion is similar to that of induction motor drives. Major alternatives such as single- and multiple-motor configurations as well as single- and multiple-speed transmissions can be found. Basically, the single-motor system configuration consists of a PM brushless motor, a voltage-fed inverter, an electronic controller as well as reduction and differential gears.

Control of PM synchronous motors can be similar to that of induction motors and the control strategies for induction motors, such as variable-voltage variable-frequency (VVVF) and field-oriented control (FOC), are still applicable. Moreover, by incorporating the well-known *d–q* coordinate transformation, the well-developed flux-weakening control technique can readily be applied to these motors for constant-power operation (Sato *et al.*, 1997).

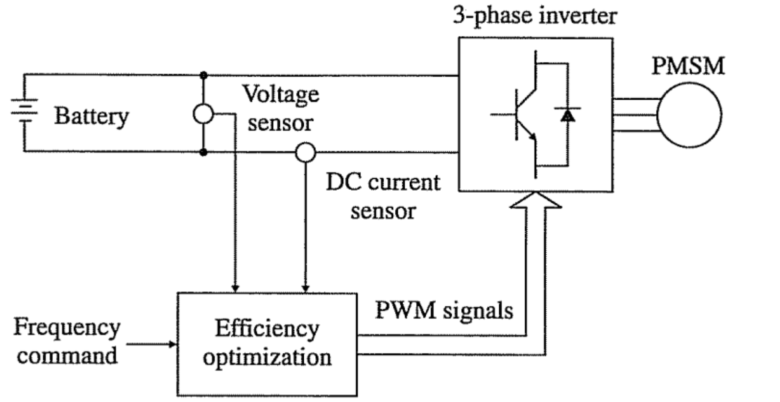


Fig. 5.44. Self-tuning efficiency-optimizing control of a PM synchronous motor drive.

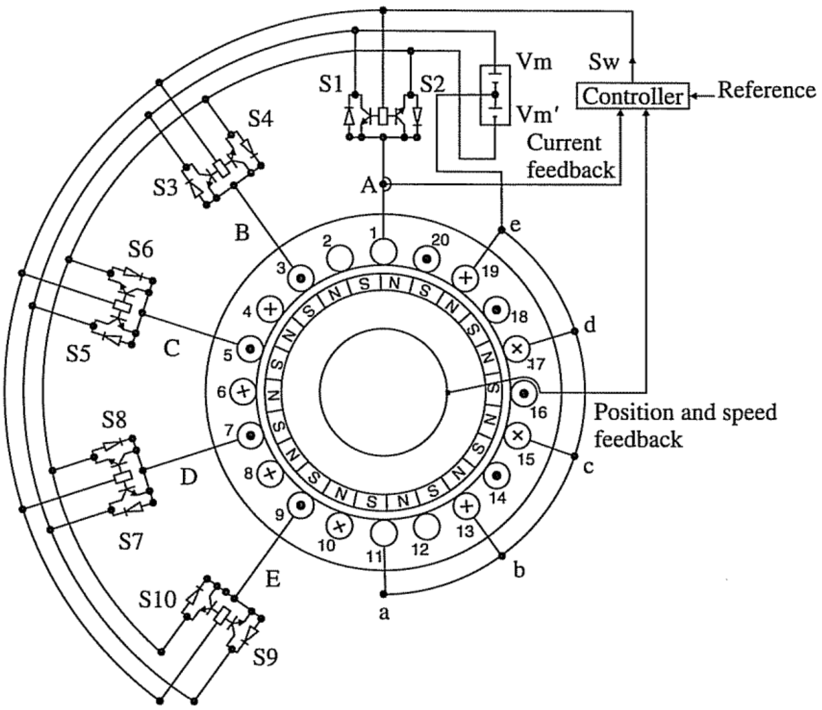


Fig. 5.46. Phase-decoupling brushless dc motor drive.

5. Switched Reluctance Motor Drives

Although the earliest recorded switched reluctance (SR) motor was built to propel a locomotive in 1838, SR motor drives could not realize their full potential until the advent of modern power electronics and powerful computing facilities.

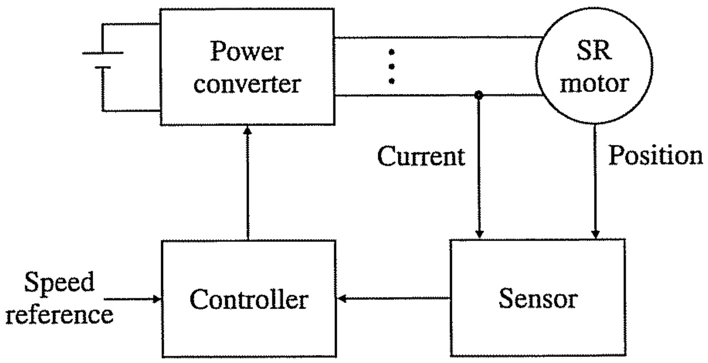


Fig. 5.54. Basic structure of SR motor drives.

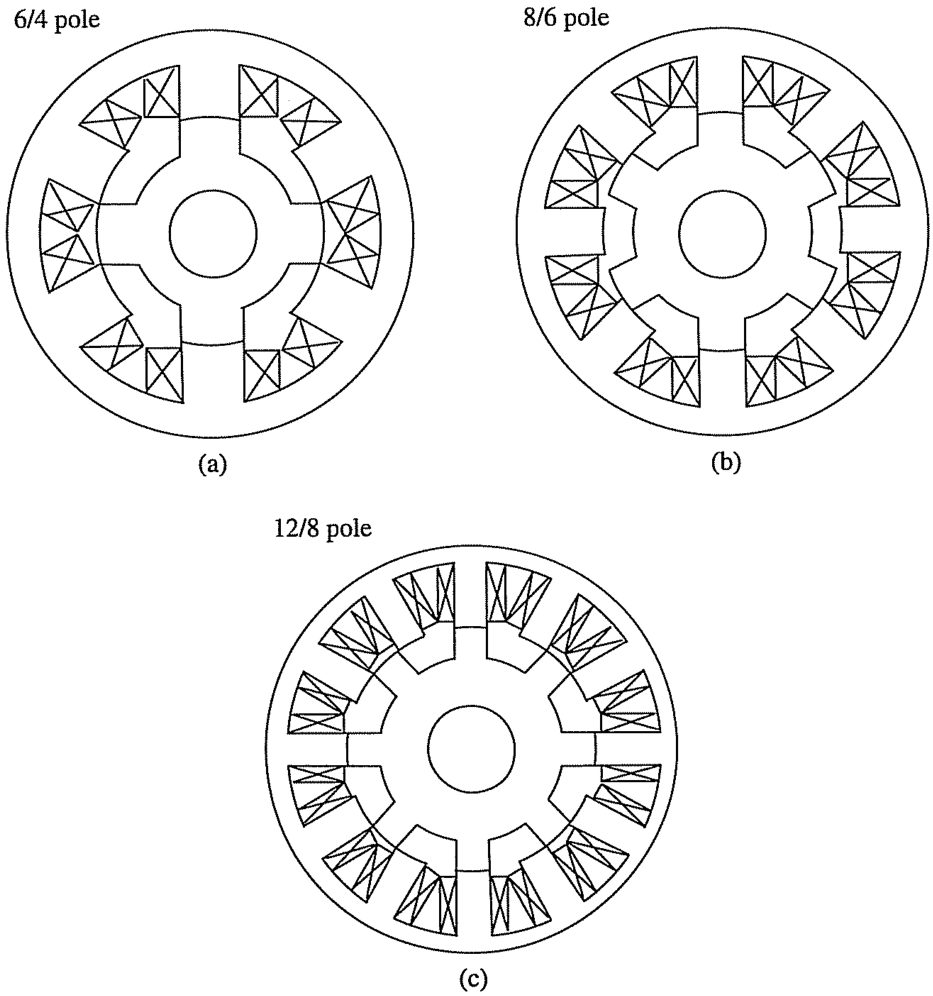


Fig. 5.55. Basic structure of SR motors.

According to the co-energy principle (Miller, 1993), the reluctance torque produced by one phase at any rotor position is given by:

$$T(\theta, i) = \frac{\partial W'(\theta, i)}{\partial \theta},$$

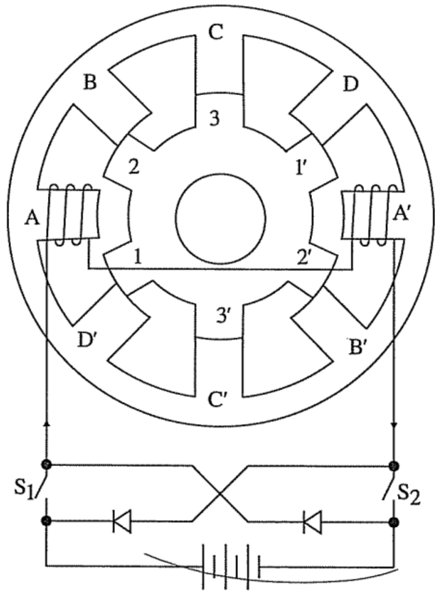


Fig. 5.56. Four-phase 8/6-pole SR motor drive.

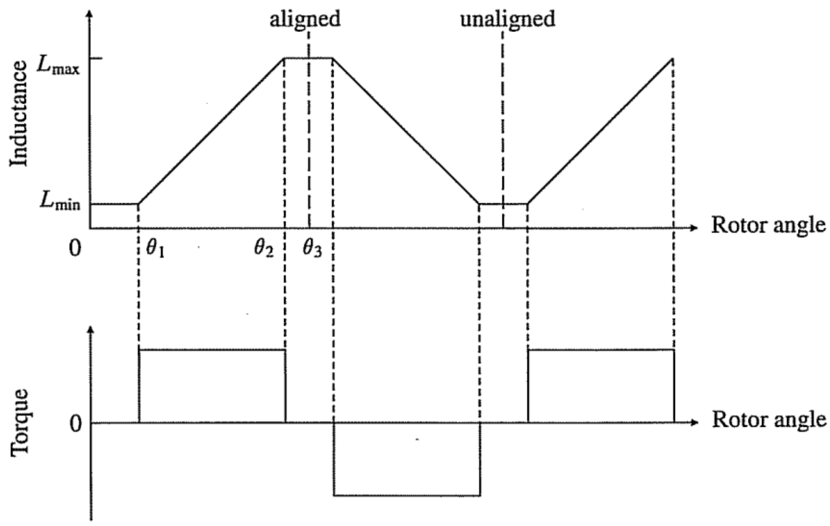


Fig. 5.57. Variations in inductance and constant-current torque vs. rotor position.

where θ is the rotor position angle, i is the phase current and $W'(\theta, i)$ is the so-called co-energy defined as the area below the magnetization curve shown in Fig. 5.58. It can be expressed as:

$$W'(\theta, i) = \int_0^i \psi(\theta, i) di.$$

Since the flux linkage $\psi(\theta, i)$ can be written as $\psi(\theta, i) = L(\theta, i)i$, it yields:

$$T(\theta, i) = \frac{1}{2}\frac{\partial}{\partial \theta}\int_0^{i^2} L(\theta, i) di^2.$$

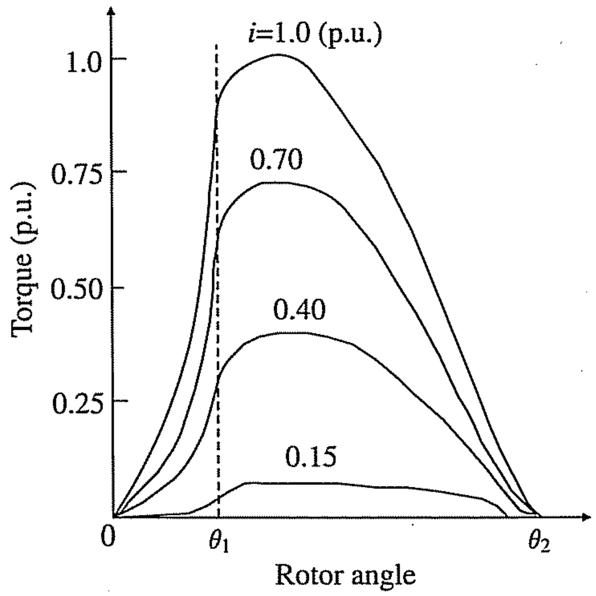


Fig. 5.61. Nonlinear torque characteristics.

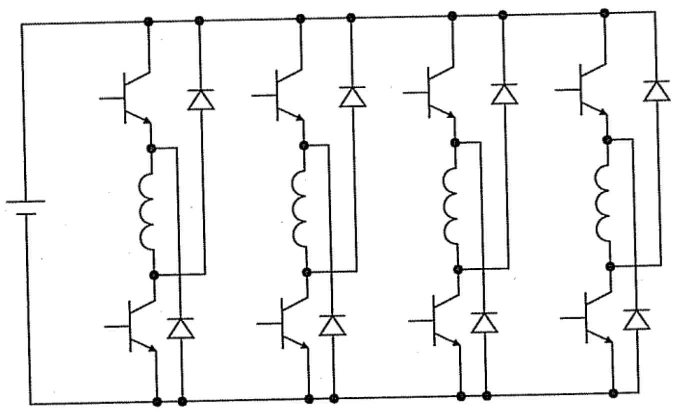


Fig. 5.64. Converter circuit of SR motor drives.

CCC

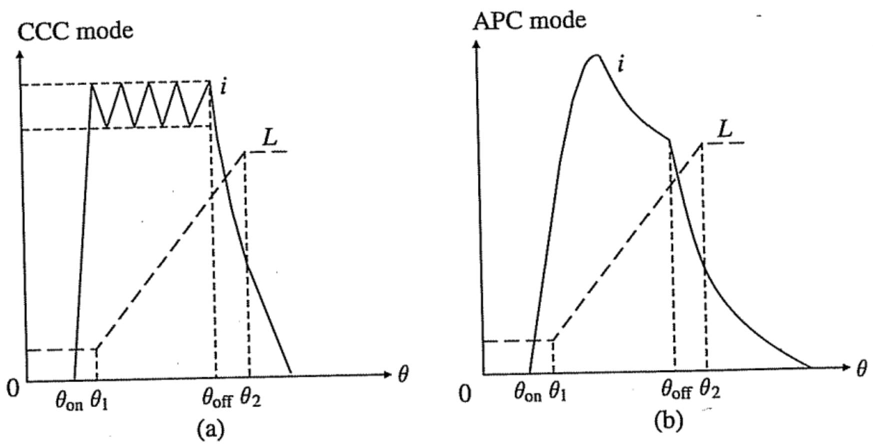


Fig. 5.63. Current and inductance waveforms in CCC and APC modes.

CCC=Current Chopping Control   APC=Angular Position Control

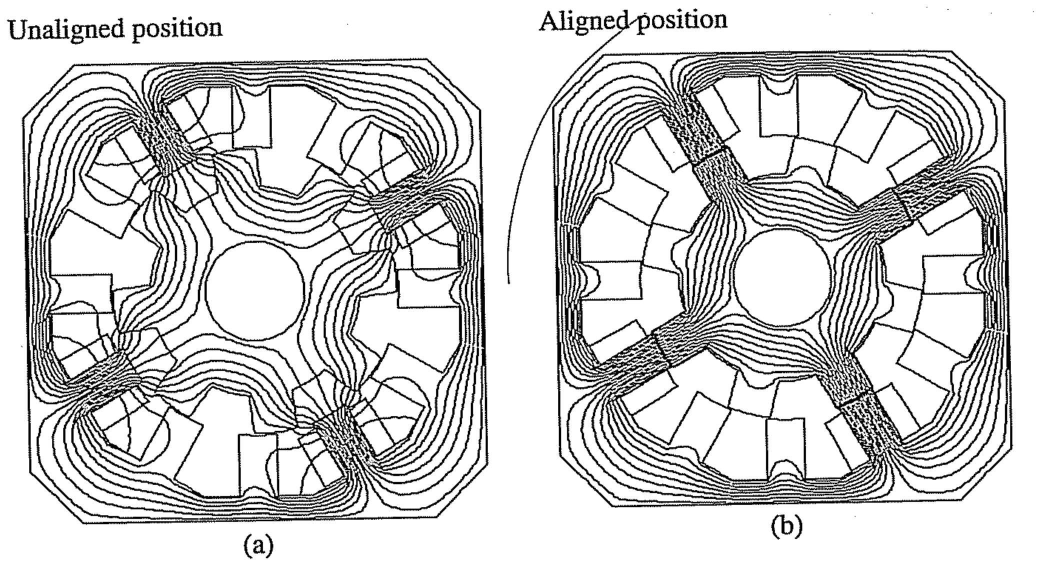


Fig. 5.65. Electromagnetic field distribution of a SR motor.

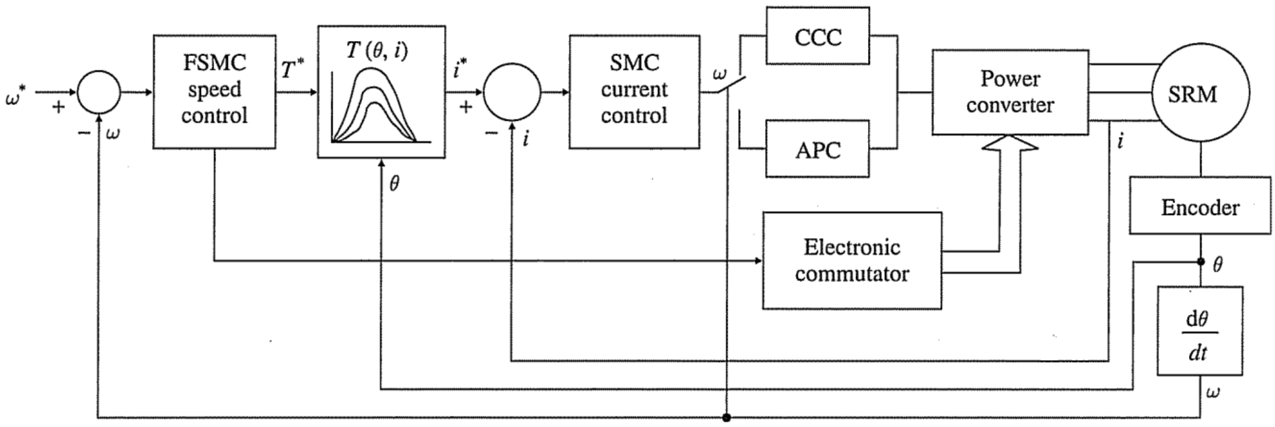


Fig. 5.66. FSMC system of a SR motor drive.

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