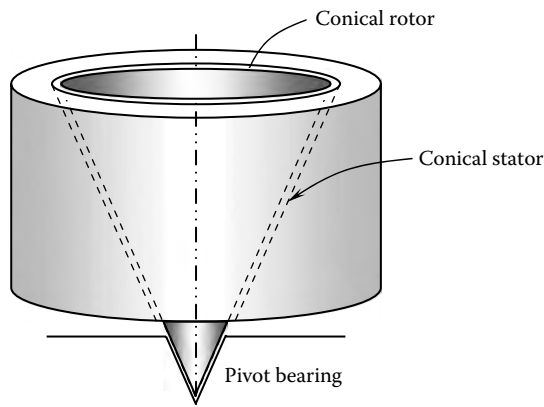
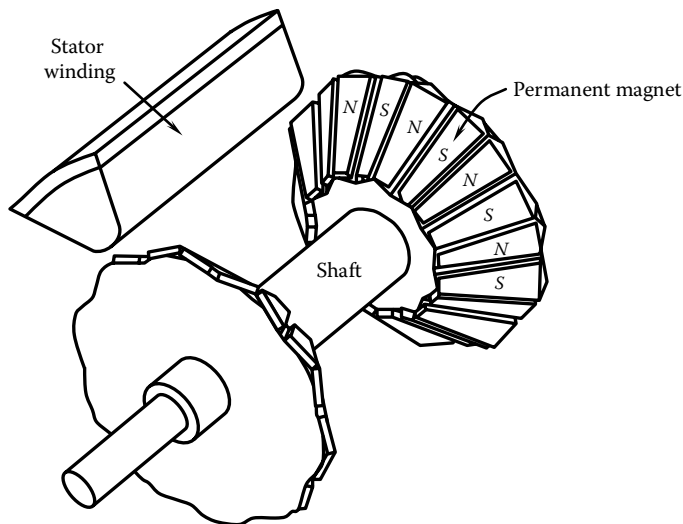


**FIGURE 12.23**

Conical rotor with a pivot bearing having a uniform air gap.

**FIGURE 12.24**

Conical rotor with PMs at two ends of the shaft and stator windings located between the PMs.

12.6 Transverse Flux Motor

Unlike RF or AF (TF) motors, TF motors have complex magnetic circuits. The concept of the TFM can trace back to 1895 as W. M. Morday applied for the first patent. TFMs have highest torque density, usually three to four times higher than conventional synchronous and asynchronous machines [12.27]. The use of TFMs in industrial manipulators may eliminate the conventionally required gears and build direct drive systems [12.28]. Due to their superior performing characteristics, TFMs are expected for direct drive systems, such as wheel motors of hybrid electric vehicle and wind turbines [12.29].

Usually, TFMs have a toroidal armature winding, carrying current parallel to the DIR. The stator core is salient and the rotor is equipped with PMs. The stator core often carries flux in three directions. This indicates that iron powder is a preferred core material.

However, the constructive geometry and topology of TFM are considerably complex in comparison with those of conventional RF motors, and no 2D symmetry exists. Because of the difficulty and complexity in manufacturing and thus high cost, TF motors today still stay in the R&D stage, leaving them a long way to go toward industrial production. Other disadvantages include torque ripples and normal force fluctuations [12.30].

TFM can be classified as surface PM TFM (SPM-TFM) and flux-concentrated TFM (FC-TFM). Comparing with the SPM-TFM, the FC-TFM has a higher torque density but more difficulty in manufacturing. PMs in a SPM-TFM are magnetized in the direction perpendicular to the DIR. By contrast, PMs in an FC-TFM are of parallel magnetization [12.31].

An FC-TFM of 56 poles with distributed three full phases is shown in Figure 12.25. The rotor comprises a plurality of PMs of opposite magnetization direction alternately and coaxially arranged around a rotating axis. A rotor pole is arranged between every two PMs. The stator has three phases coaxially arranged around the rotating axis and separated by the distance elements. A number of stator teeth face the rotor and the stator phases together with the distance elements.

Figure 12.26 depicts the single-stator winding and stator phase, where stator winding is formed as a multiturn saddle phase winding. As can be seen from the figure, the stator winding is formed as a closed loop and arranged between two teeth forming an angle θ .

The variations of torque components of the FC-TFM along the mechanical shift angle are depicted in Figure 12.27. The data are obtained from simulations using a FEM software. It shows the peak-to-peak cogging torque is about 0.09 N-m and the peak-to-peak reluctance torque is 0.4 N-m. Interaction torque is due to the interaction between the magnetic fields of PMs and armature current, which has a peak value of 0.55 N-m.

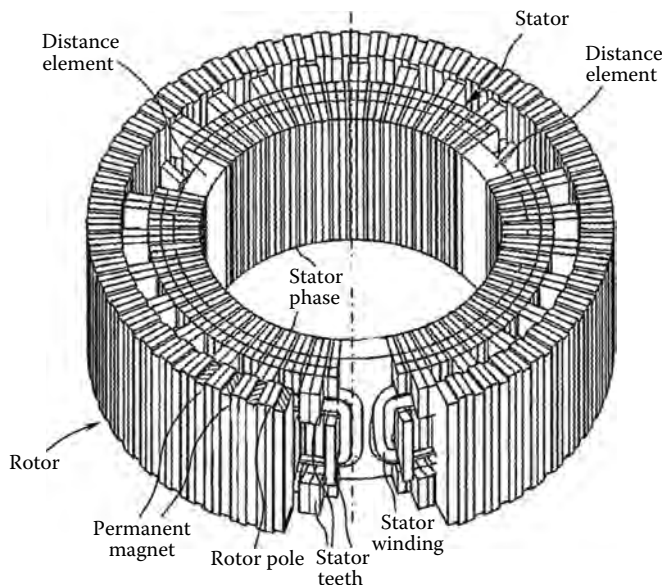
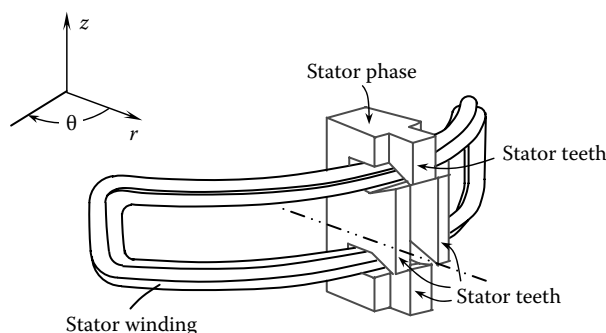
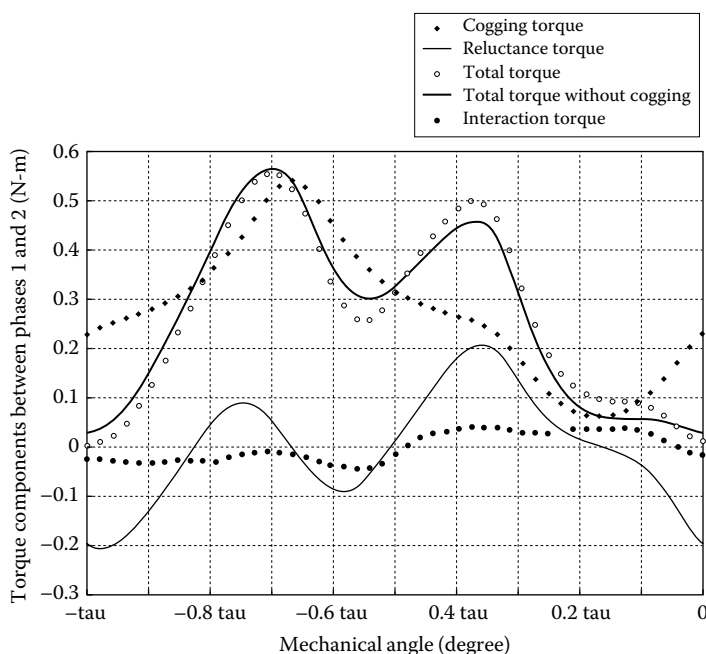


FIGURE 12.25

Perspective view of the structure of PM TF motor (European Patent 2,317,633) [12.31]. (Courtesy of the European Patent Office, Munich, Germany.)

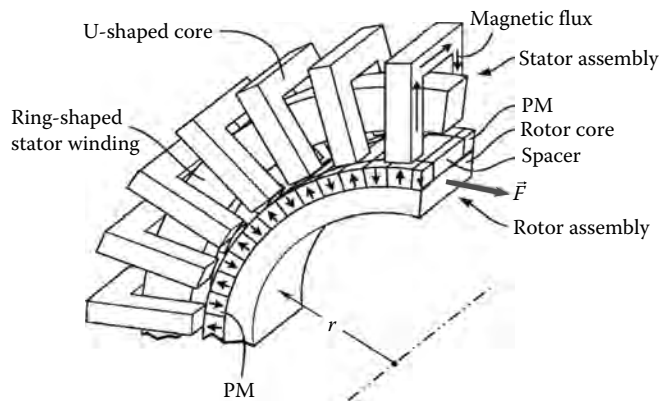
**FIGURE 12.26**

Single-stator winding and phase in an FC-TFM (European Patent 2,317,633) [12.31]. (Courtesy of the European Patent Office, Munich, Germany.)

**FIGURE 12.27**

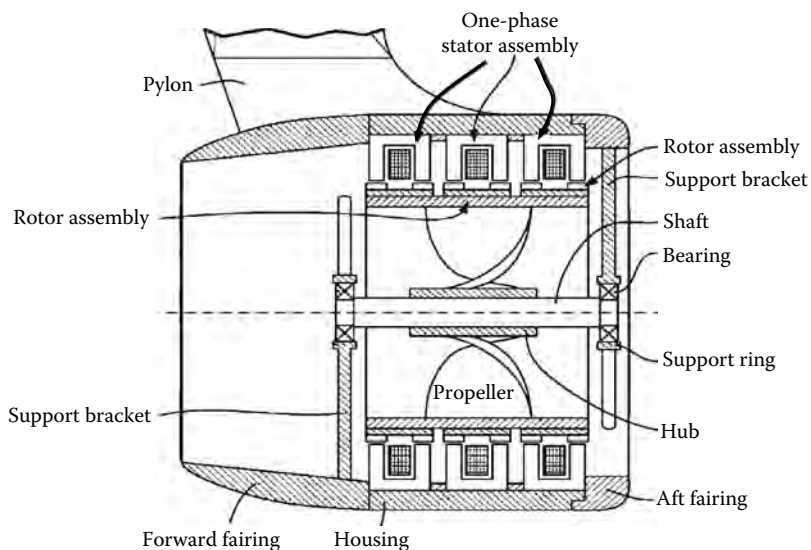
Torque component for the FC-TFM, obtained from simulations (European Patent 2,317,633) [12.31]. (Courtesy of the European Patent Office, Munich, Germany.)

Gieras and Rozman [12.32] have presented a TF motor as the rim-driven thruster (RDT). As illustrated in Figure 12.28, a one-phase unit consists of a rotor assembly and a stator assembly. The stator assembly includes a ring-shaped winding and a stator core, which comprises a number of U-shaped cores. The rotor assembly includes a rotor core, spacer, and a plurality of PMs. As shown in the figure, PMs with the opposite magnetic polarity are disposed alternately along forward and aft surfaces of the spacer. PMs are configured to have the magnetic pole orientations extending radially, either inward or outward. The magnetic flux induced in U-shaped cores interacts with the pole orientations of PMs to generate the force vector $\vec{F}$ in the tangential direction of the rotor.

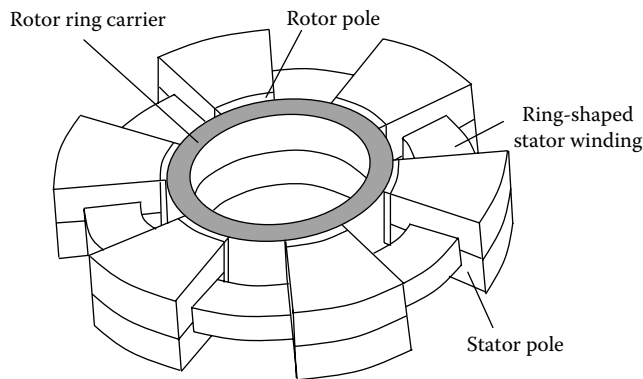
**FIGURE 12.28**

A partial perspective view of rotor and stator assembly of one-phase unit in a PM excited TF motor (U.S. Patent 8,299,669) [12.32]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)

Figure 12.29 depicts the structure of an RDT, which contains three identical one-phase units to form a three-phase, TF motor. The RDT includes the housing, forward and aft fairing, stator assemblies, rotor assemblies, and propulsion assembly. The propellers are connected with the rotor. The rotor shaft is supported by two bearings at its ends. While electric current within stator windings causes magnetic flux to flow through the stator cores, the oppositely oriented magnetic poles of PMs cause magnetic flux to travel through rotor assemblies. The interaction between these magnetic fluxes applies a torque to the rim. The bearings permit the rim and rotor assembly to rotate smoothly about the centerline.

**FIGURE 12.29**

Structure of an RDT with a TF motor (U.S. Patent 8,299,669) [12.32]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)

**FIGURE 12.30**

A 3D overview of a six-pole TF reluctance machine.

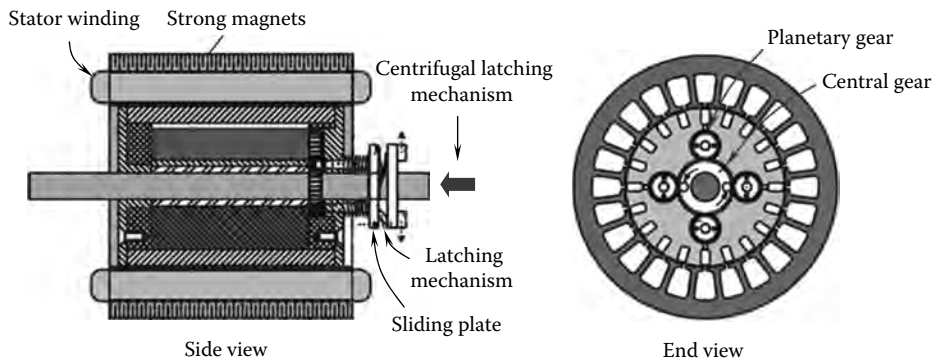
The TF reluctance (TFR) machine is a variant of the TFM with a passive rotor [12.33]. As shown in Figure 12.30, a ring-shaped toroidal stator winding is surrounded by a number of U-shaped salient poles. The main differences compared with an SRM are as follows: (1) The TFR motor has a homopolar-type stator phase winding. (2) Its phase modules are placed consecutively in the axial direction. (3) It has the same number of salient poles on the rotor and stator. (4) Each phase of the motor is an independent module. In TFM technology, it is preferable to employ a plurality of TFMs arranged in tandem for reducing torque ripples, avoiding the start-up difficulties, and obtaining continuous rotation. Generally, the motor must have three or more than three phases.

12.7 Reconfigurable Permanent Magnet Motor

The quest for high-efficiency electric motors has stimulated many novel ideas in new types of motor design. One of the latest is to push the efficiency of electric motors to above super-premium level by employing reconfigurable rotor magnets.

The reconfigurable magnet technique can stabilize the output of the machine spinning even at variable speeds. This might be especially useful for some applications. For instance, a wind turbine built with this technique can generate constant output from variable wind speeds without the use of intermediate inverters [12.34].

A reconfigurable PM motor is shown in Figure 12.31 [12.35]. Each of the four PMs is attached to a planetary gear that engages with the central gear. All the four magnets remain rotationally aligned. The motor is reconfigurable from an asynchronous mode at the start-up into a more efficient synchronous mode thereafter. The motor includes a squirrel cage for IM operation at the start-up with the PMs positioned to produce a weak magnetic field not interfering with the start-up. During the start-up, the centrifugal latching mechanism retains the PMs in the weak magnetic field position. When the motor reaches a sufficient speed, the PMs are released by the centrifugal mechanism and rotate to produce a strong magnetic field in harmony with the rotating stator magnetic field for the efficiency synchronous operation.

**FIGURE 12.31**

A cross-sectional view of reconfigurable magnet motor, revealing the details of the centrifugal clutch used to rotate the rotor magnets once the motor is reaching a certain speed (U.S. Patent 8,390,162) [12.35]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)

More detailed description of the transition between a weak magnetic field and a strong magnetic field applied to the motor is presented in Figure 12.32. The centrifugal latching mechanism includes weights, rotating plate, spring disk, sliding plate, pins, and pin seats. The weights and spring disk are designed so that when the motor is stationary, the weights remain in the inward position to the shaft and the magnets are at the weak magnetic field position. Meanwhile, the pins engage the pin seats in the central gear when the motor is at rest and the centrifugal latching mechanism holds the PMs in the weak magnetic field position. At an appropriate rotating speed, the weights move outward due to the centrifugal force, causing the spring disk to snap axially from the extended position as in Figure 12.32a to the retracted position as in Figure 12.32b. The centrifugal latching mechanism thus pulls the pins from the pin seats releasing the PMs to the strong magnetic field position. As the motor stops, the PMs are magnetically urged back to the weak field position again.

12.8 Variable Reluctance Motor

VRMs have been widely used for high-torque applications. Their inherent fault-tolerant features and other advantages have made them a prime candidate for reliability-premium applications. From the standpoint of energy conversion, VRM is unique compared to other types of motors.

According to the relationship of motion plane and flux plane, VRMs can be categorized as the transverse-flux machine (TFM) and the vernier machine (VM). As addressed previously, due to the complexity of the constructive geometry, the design and fabrication of the TFM are considerably difficult. By contrast, VMs can adopt a simple toothed-pole-stator and PM-rotor configuration. Each stator tooth is split into small teeth at the end (i.e., flux-modulation poles). Thus, a small movement of the PM rotor can cause a large movement of flux linkage in the stator armature winding [12.36].

Figure 12.33 shows an outer-rotor, flux-controllable vernier PM motor, designed for the in-wheel drive of electric vehicles. In this design, the inherent outer-rotor topology makes

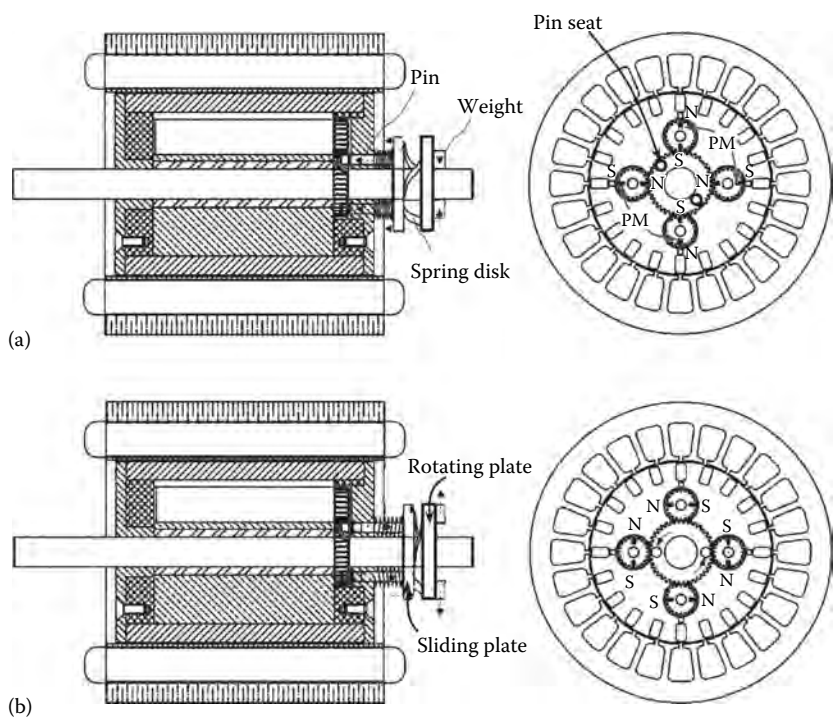


FIGURE 12.32 The side and end views of the reconfigurable electric motor with the centrifugal latching mechanism: (a) in the weak magnetic field position when the four PMs are held by the centrifugal latching mechanism and (b) in the strong magnetic field position when the four PMs are released by the centrifugal latching mechanism (U.S. Patent 8,390,162) [12.35]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)

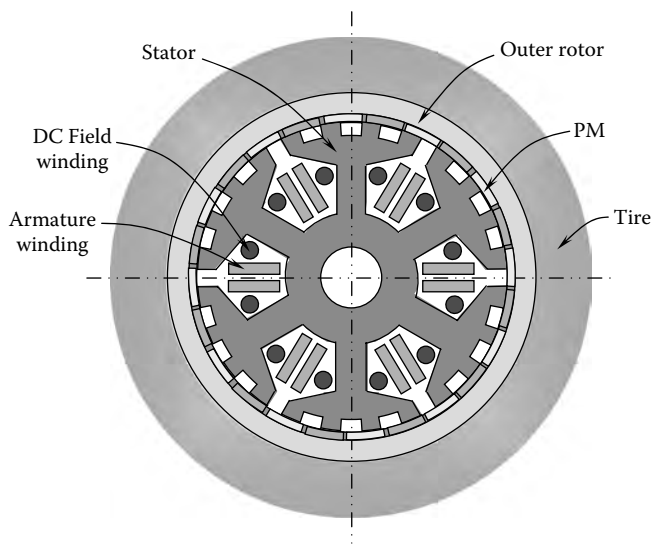


FIGURE 12.33 Configuration of vernier PM motor used as in-wheel drive.

the motor directly connect with the wheel rim and eliminates the mechanical transmission. The inner stator accommodates two sets of windings, that is, the three-phase armature windings and the DC field windings for performing the flux weakening control at high-speed operation. There are 24 salient poles, setting up in the inner stator for performing the flux modulation. Twenty-two pole pair PMs are mounted on the outer rotor. The key of the design is to use the vernier structure for obtaining the high-speed to low-speed gear effect and achieving the high output torque at low-speed operation [12.37]. This direct drive, in-wheel motor can smoothly operate within the speed range of 0–1000 rpm at different operation modes for electric vehicles.

According to excitation patterns, doubly salient motors (DSMs) can be classified into three types: PM, fielding winding, and hybrid. The VRMs deploying doubly salient structures (i.e., teeth on both the stator and rotor) have been developed for several decades with well-explored design features, torque production, and control characteristics. In recent years, doubly salient PM (DSPM) motors have gained renewed interest for some new applications, particularly in-wheel motors for electric vehicle drives.

Figure 12.34 shows the structure of a 12/8-pole (the stator pole number $p_s = 12$ and the rotor pole number $p_r = 8$) DSPM motor. Armature windings are located in the stator. Four pieces of PM are located radially at the four corners of the stator. This indicates that the leakage flux outside the stator circumference (which is generally neglected in conventional PM motors) becomes significant. Hence, to take the leakage flux into account, the design domain must be extended from the stator circumference to the surrounding space. Since the rotor consists of only silicon steel laminations, it gives motor the capability to work at very high speeds.

In order to minimize the switch frequency and hence the iron losses in poles and yokes, the number of rotor poles p_r should be selected as small as possible but must be equal to or larger than three for the capability of self-starting. As a result, the rotor poles are usually less than stator poles. In practice, p_s/p_r of 6/4, 8/6, and 12/8 are possible configurations of DSPM motors. Generally, 12/8 pole motors have less iron losses and magnetic potential drop than 6/4 pole machines [12.38].

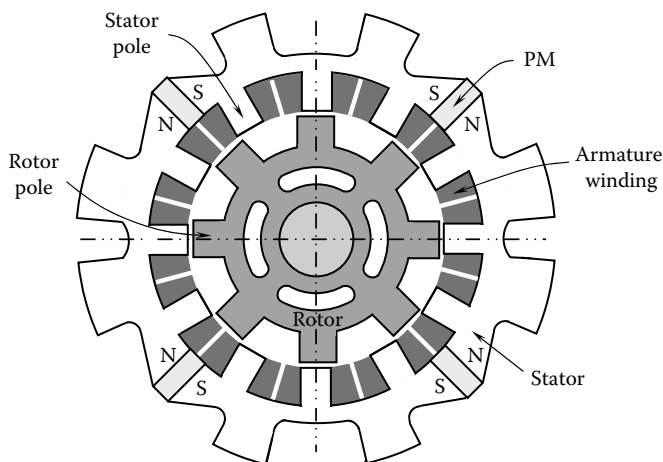


FIGURE 12.34

The cross-sectional view of a 12/8-pole DSPM.

From the investigation of DSPM motor by Cheng et al. [12.39], the following may be concluded: (1) Although the DSPM motor has salient poles in the stator and rotor, the PM torque significantly dominates the reluctance torque, exhibiting low cogging torque. (2) The air gap flux of the DSPM motor is mainly contributed by PMs, whereas the armature current contributes to the change of the flux distribution. (3) Because most of the armature flux loops through the adjacent stator poles, instead of PMs, the DSPM motor is less sensitive to demagnetization than other PM motors. (4) The inductance of the DSPM motor depends not only on the rotor position but also on the strengthening/weakening action of the armature field to the PM field. (5) The leakage flux outside the stator circumference of the DSPM motor may lead to a reduction in the effective flux of about 3%.

12.9 Permanent Magnet Memory Motor

Ostovic first proposed the innovative concepts of PM memory motors, which can be built either as variable flux memory motors (VFMMs) [12.40] or as pole-changing memory motors (PCMMs) [12.41]. Memory motors combine the flux controllability of PM motors and the employment of the flux concentration principle that enables creating air gap flux densities for high-efficiency machines.

12.9.1 Variable Flux PM Memory Motor

Unlike the conventional PM motors, the type of VFMM has the distinct ability to change the intensity of magnetization by short pulses of stator current and to memorize the flux density level in the rotor PMs. Additional advantages include high efficiency, high torque-to-weight ratio, large starting torque, full controllability of back EMF, no risk of demagnetization by the load current, zero reactive power demand on stator terminals, simple structure, and operation in a wide speed range without excessive rotor I^2R losses. In fact, VFMM is the only synchronous machine with rotor excitation that has a true speed capability without sacrificing the other machine properties. However, compared with other types of PM motors, this type of motor may have relatively low overload ability and reliability [12.42].

As shown in Figure 12.35, a four-pole VFMM consists of trapezoidal alnico PMs sandwiched by soft irons. Both the PMs and soft irons are sandwiched by triangle-shaped plates made of a nonmagnetic material. All of these components are mechanically fixed to a nonmagnetic shaft. PMs can be online magnetized or demagnetized with various magnetization levels. Tangentially magnetized PMs with red and blue represent N-poles and S-poles, respectively. The magnetic flux $\Phi_{\max}$ is driven by the PMs to transit across the air gap into the stator, continuously go along the circumferential direction in the stator core, and finally come back through the air gap into the rotor for completing the loop.

VFMMs combine the advantages of a wound rotor synchronous motor (simple control of induced voltage) and a PM synchronous motor (no excitation losses), resulting in a unique synchronous machine for numerous applications.

12.9.2 Pole-Changing PM Memory Motor

Conventional PM machines have a constant number of poles, because their magnets are incorporated into rotor body in a manner that does not allow any change of machine

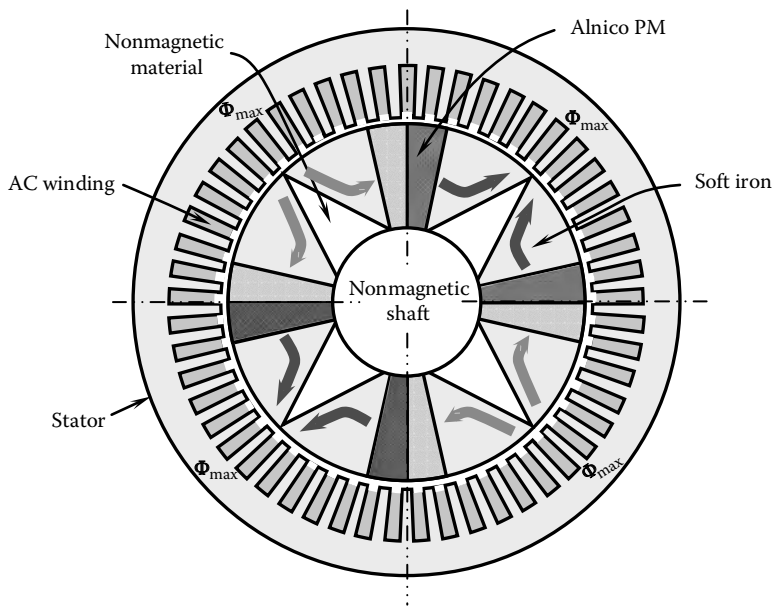


FIGURE 12.35
The cross-sectional view of a fully magnetized, PM VFMM.

topology. By comparison, a pole-changing PM memory motor has the capability to change the number of poles. This type of motor has several advantages such as high efficiency, high output power, and less thermal dissipation issue due to the lack of rotor copper losses. These make pole-changing memory motors attractive for many motor applications, among which the fan and pump applications are the most pronounced.

Figure 12.36 depicts the operational principle of an eight-pole magnetized PCMM. Due to the geometry symmetry, only a quarter of the motor is modeled. The motor contains 32 magnets positioned radially in the stator. Each pole takes a 45° sector, which contains four PMs ($32/8 = 4$). All of the PMs are magnetized in the tangential direction. The rotor wreath is built of PMs along with soft iron segments and is mechanically fixed to a nonmagnetic shaft.

After the stator windings are reconnected into a six-pole (a 60° sector per pole) configuration, a short pulse of stator current changes the rotor from eight-pole to six-pole magnetization (Figure 12.37). Since the number of magnets per pole is no longer an integer ($32/6 = 5.33$), some magnets may remain demagnetized, as shown in the figure. As a matter of fact, both flux per pole and stator current necessary to remagnetize the rotor magnets vary as a function of the number of magnets per pole. Therefore, by changing the pole number, these two important motor parameters are adjusted for optimizing motor performance.

12.9.3 Doubly Salient Memory Motor

DSPM memory motors are the combination of memory motors, namely, the online tunable flux-mnemonic PMs and DSPM motors, thus achieving effective air gap flux control. Employing the outer-rotor and double-layer-stator topology, the motor takes advantage of compact structure, low armature reaction, and direct drive capability. This type of motor can offer the unique features of pole dropping and pole reversing [12.43].

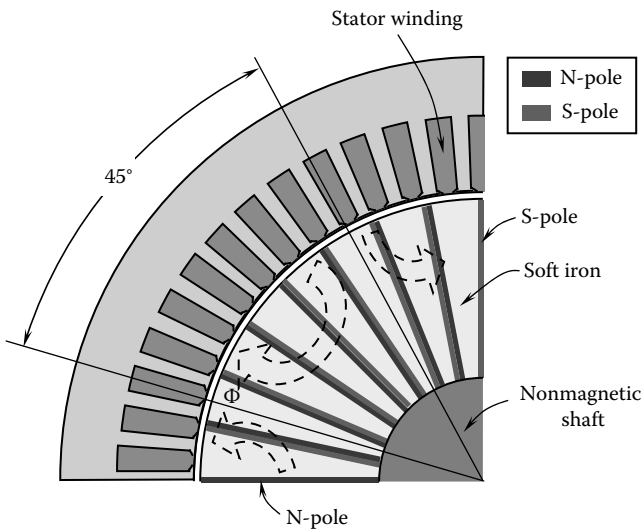


FIGURE 12.36
The cross-sectional view of an eight-pole PM magnetized PCMM.

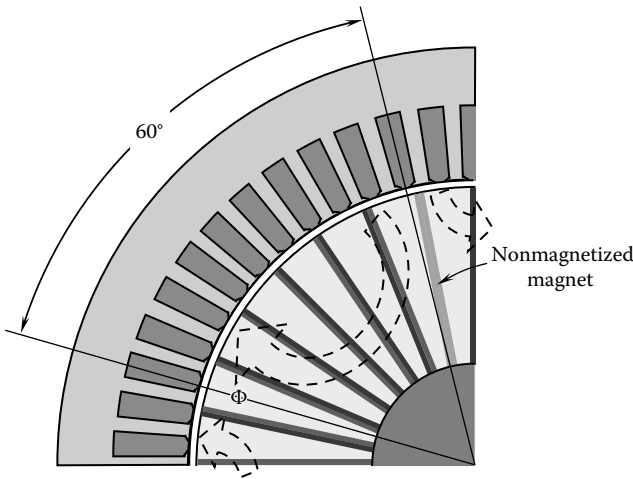


FIGURE 12.37
The cross-sectional view of a six-pole PM magnetized PCMM.

The topology of the doubly salient memory motor is depicted in Figure 12.38. It adopts an outer-rotor, an outer-layer-stator, and an inner-layer-stator structure. The motor has five-phase and 30-pole/24-pole doubly salient structure on the stator/rotor. The outer rotor only consists of lamination iron and thus offers excellent mechanical robustness. This arrangement is especially suitable for the direct drive applications such as electric vehicle in-wheel motors and wind turbines. The AC armature windings and DC magnetizing windings are located at the outer-layer stator and inner-layer stator, respectively. This effectively uses the space of the stator yoke. Alnico PMs are fixed between the inner-layer

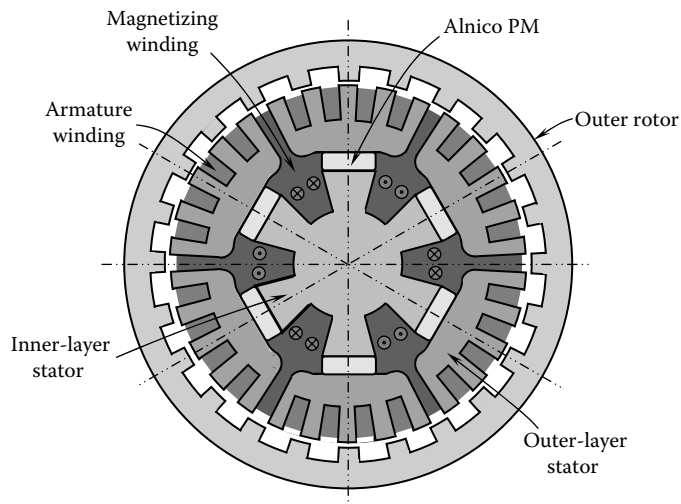


FIGURE 12.38
Topology of doubly salient PM memory motor.

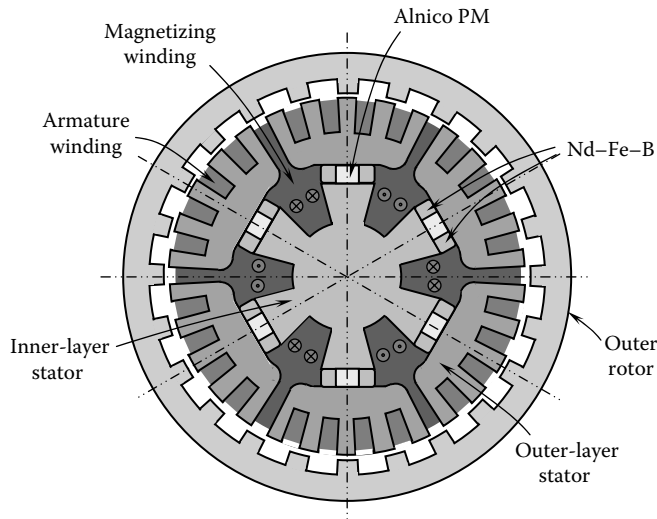
stator and outer-layer stator. The using of alnico PMs can achieve a controllable air gap flux by applying temporary current pulses to the magnetizing winding to online tune the magnetization level of alnico PMs.

Compared with other types of PMs, alnico magnets exhibit good temperature stability and resistance to corrosion, high Curie temperature (approximately 840°C), but a low coercivity, which is prone to demagnetization due to shock. Furthermore, alnico magnets deliver smaller energy products than rare-earth PMs, thus degrading the machine power density. In order to address these problems, Li et al. [12.44] have presented a new flux-mnemonic dual-magnet machine that incorporates both the Nd-Fe-B and alnico PMs for providing hybrid excitation (Figure 12.39). In such a way, the proposed machine not only retains the feature of online tunable air gap flux control but also improves the machine power density.

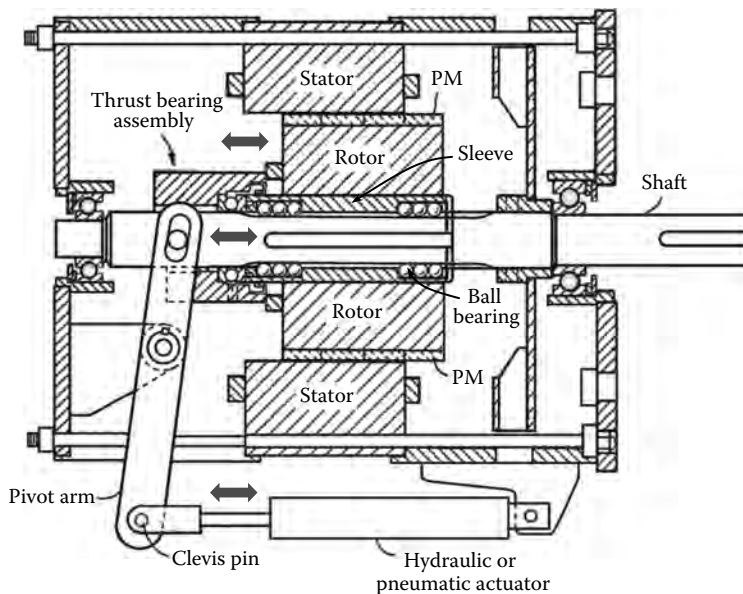
12.10 Adjustable and Controllable Axial Rotor/Stator Alignment Motor

In a conventional RF motor, the relative position between the rotor and stator is fixed both axially and radially. In this novel PM motor, the axial alignment between a rotor and a stator is adjustable and controllable using a mechanical technique. As the PM motor is offset axially to provide axial misalignment between the rotor PM poles and the stator, the effective magnet pole strength or magnetic flux to the stator are significantly reduced, resulting in an increase in speed and a decrease in motor torque [12.45].

As shown in Figure 12.40, the stator is incorporated into the motor housing structure. PMs are mounted on the outer surface of the rotor. The rotor is connected with a hydraulic or pneumatic actuator through a pivot arm at its end. A rotor sleeve is coupled to the rotor with a plurality of parallel grooves formed on the inner surface. The grooves have

**FIGURE 12.39**

Doubly salient PM memory motor with dual magnet.

**FIGURE 12.40**

Structure of PM motor with adjustable axial rotor/stator alignment (U.S. Patent 6,555,941) [12.45]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)

a semicircular cross-sectional shape and are configured to receive a plurality of ball bearings. Correspondingly, the motor shaft also has a plurality of parallel grooves formed at the outer surface. The ball bearings are contained within the channel formed by both the rotor sleeve and shaft grooves. Thus, the rotor is allowed to slide axially via the ball bearings when the hydraulic or pneumatic actuator is activated.

The rotor in Figure 12.40 is about 25% disengaged with the stator. This amount of misalignment will produce an increase in speed of approximately 150% of the rated speed.

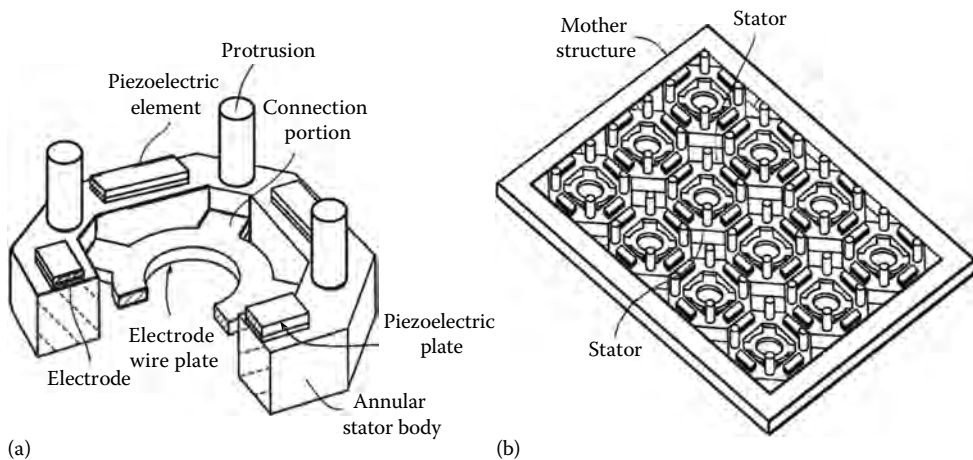
12.11 Piezoelectric Motor

Piezoelectric effect refers to the phenomenon that when a certain nonconducting material, such as quartz crystal (SiO_2) and ceramics, is subject to mechanical stress (e.g., pressure or vibration), the material generates an electric potential across it. Conversely, when an electric field is applied to the material, it undergoes mechanical distortion or vibration.

Piezoelectric motors operate based on the principle of piezoelectric effect. In a piezoelectric motor, the piezoelectric material produces high-frequency (inaudible to the human ear) acoustic vibrations on a nanometer scale to create a linear or rotary motion. Piezoelectric motors have a number of potential advantages over conventional electromagnetic motors, including the following [12.46]:

- Piezoelectric motors maintain high torque at low speed with a compact motor size. Hence, they have higher torque densities compared with conventional electromagnetic motors for the same power rating.
- This type of motor does not create electromagnetic fields, nor is affected by external electromagnetic fields. This feature is extremely important for motors used within strong magnetic field environments.
- Because of the direct drive mechanism, piezoelectric motors eliminate the need for supplementary transmissions or gear trains found in conventional electromagnetic motors. This avoids the usual backlash effects in conventional motors and thus increases the motor positioning accuracy.
- A compelling advantage of piezoelectric motors is their intrinsic steady-state autolocking capability as the driving mechanics use friction between the vibrating stator and rotor.
- With less heat generated in piezoelectric motors, cooling is no longer a critical issue in motor design.
- This type of motor has a low rotor inertia and thus provides rapid start and stop characteristics.
- With fewer mechanical components, their construction is relatively simple. Thus, piezoelectric motors are well suited for miniaturization, and their overall efficiency is relatively insensitive to size.
- In the power-off mode, the position can be maintained due to the frictional force between the contact surfaces.
- Piezoelectric motors have quiet operation.

Piezoelectric motors are generally used in low-torque and high-precision micropositioning applications, such as medical devices, robotic positioning, pharmaceuticals handling, and pick-and-place assembly.

**FIGURE 12.41**

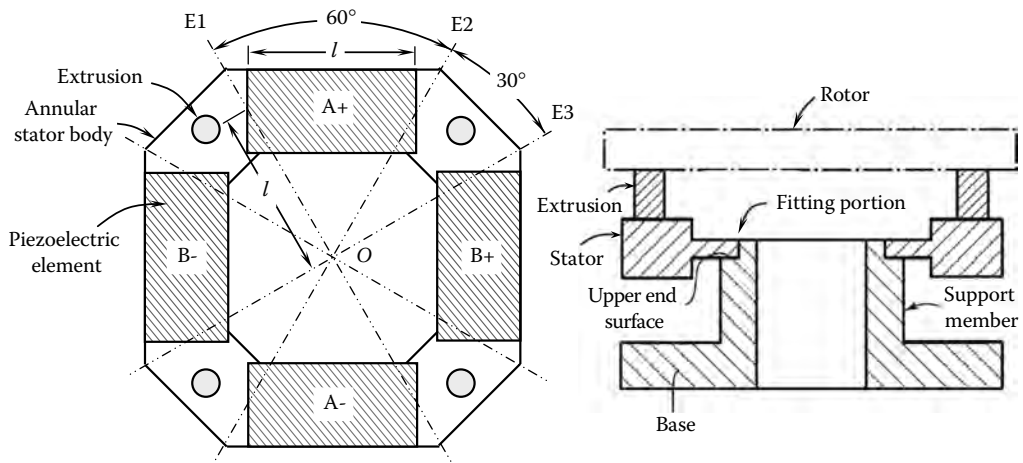
The structure of a piezoelectric motor: (a) a partially cross-sectional perspective view of the stator used in a piezoelectric motor and (b) the mother structure prepared obtaining the stators (U.S. Patent 8,330,326) [12.47]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)

The structure of a piezoelectric motor is presented in Figure 12.41 [12.47]. A stator includes a substantially annular stator body on which a number of piezoelectric elements are mounted. Each piezoelectric element consists of a piezoelectric plate made of ceramic, electrodes formed on the surfaces of the piezoelectric plates. A number of protrusion standings between adjacent pairs of the piezoelectric elements are in contact with the rotor for actuating the rotor (Figure 12.41a). Figure 12.41b shows the mother structure, containing 12 identical stators, each of them equipped with a plurality of piezoelectric elements. The electrodes and wiring lines may be formed by coating and backing an electroconductive paste or be formed as part of the cofiring process for making the mother structure. Then, the mother structure is cut in the thickness direction, so that each individual stator has the same structure as the stator shown in Figure 12.41a. In such a way, the stator can be assembled with a rotor for forming a piezoelectric motor.

Figure 12.42 is a schematic view illustrating the driving principle of the piezoelectric motor. Two pairs of piezoelectric elements facing each other, that is, A+ and A− and B+ and B−, are polarized in opposite thickness directions. A+ and A− constitute an A-phase, while B+ and B− constitute a B-phase. The symbols A+ and A− indicate that the piezoelectric bodies are polarized in opposite thickness directions. So does the B-phase drive.

Imaginary lines connect the center point O and midpoints of the short sides of the piezoelectric elements, with the length l . The angle between the imaginary lines E1 and E2 is about 60° . This indicates that the length of the piezoelectric element equals the length l . Thus, three standing waves are excited and combined to generate three progressive waves. When the central angle corresponding to the wavelength of the three progressive waves is λ_0 , the length l corresponds to the central angle of $\lambda_0/2$.

When the piezoelectric motor is driven and a progressive wave is generated in the substantially annular stator body made of an elastic member, the ends of the protrusions perform elliptical motion. Therefore, the rotor, which is in close contact with the protrusions, is rotated.

**FIGURE 12.42**

The driving principle of the piezoelectric motor (U.S. Patent 8,330,326) [12.47]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)

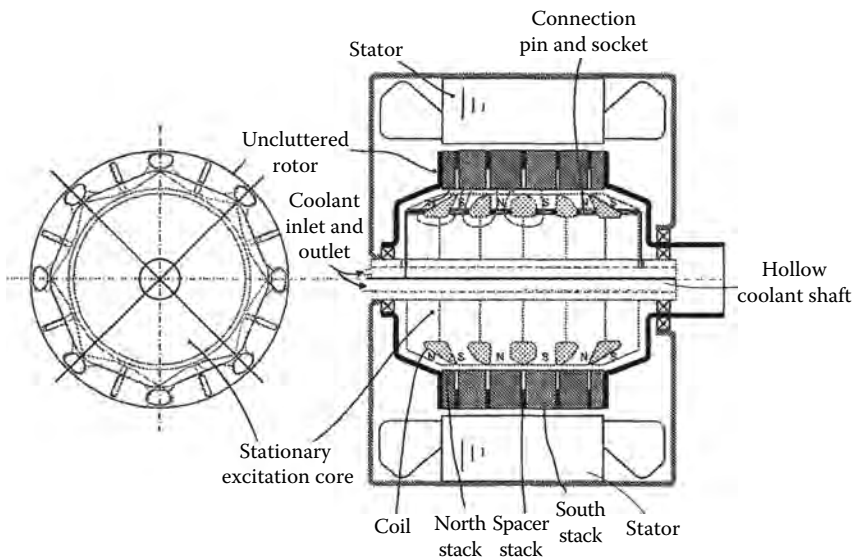
12.12 Advanced Electric Machines for Renewable Energy

As pointed by Chau et al. [12.36], the latest development of renewable energy machines is focused on three directions: the PM machine aiming to achieve high reliability and high robustness, the direct drive PM machines aiming to directly harness the renewable energy without any transmission mechanism, and the magnetless machines aiming to avoid using expensive rare-earth PMs. Among them, the magnetless machines are the most attractive to the energy industry.

In the last several years, the global price of rare-earth magnets has risen significantly, and consequently, it greatly increases the manufacturing costs of PM motors. This price soar has motivated motor engineers and material scientists to develop new types of electric machines without using magnets and to discover alternatives of rare-earth magnets.

The scientists at a US national laboratory have developed a PM-less synchronous reluctance motor [12.48]. As presented in Figure 12.43, the PM-less motor consists of a stator that generates a magnetic revolving field when sourced by an AC and an uncluttered rotor that is disposed within the magnetic revolving field and spaced apart from the stator to form an air gap. The rotor includes a plurality of rotor pole stacks having an inner periphery biased by single polarity of an N-pole field and an S-pole field, respectively. The outer periphery of each of the rotor pole stacks is biased by an alternating polarity.

Without PMs, some of these brushless synchronous machines may have a reduced size, lower weight, and less core losses. In hybrid vehicle applications, there may be little or no core losses when the system runs free without field excitations. Without a magnetic resistance, fuel efficiency may increase. In these systems, the stator fields can be cut off to enhance safety, fields can be boosted to increase or reach peak acceleration power in short time periods, power factors may be optimized (e.g., lowering the loading in inverter applications), and efficiency maps may increase due to the adjustable fields.

**FIGURE 12.43**

Cross-sectional view of the PM-less electric motor (U.S. Patent 8,264,120) [12.48]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)

Figure 12.44 illustrates in more detail the eight-pole rotor stacks that are used to form an uncluttered rotor. The stack is made of laminations. The number of magnetically isolated channels is equal to the number of poles that are equally spaced apart on the outer periphery. While the polarity along the outer peripheral surface is arranged alternately, the inner circumference of each of the north and south polarity pole stacks maintains a common polarity (Figure 12.44a and b). The inner polygonal surfaces of the spacer stacks maintain a neutral polarity (Figure 12.44c). The magnetically isolated channels in the spacer stacks are equally spaced about its annulus.

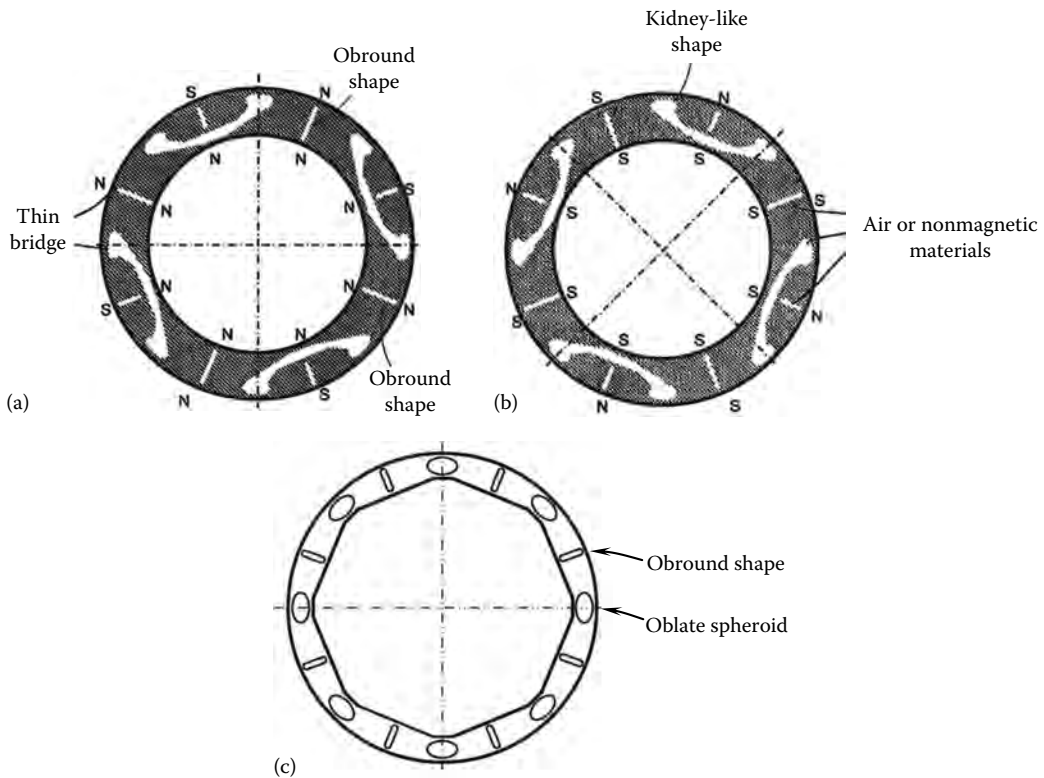
12.13 Micromotor and Nanomotor

The rapid development of microtechnology and nanotechnology has triggered vast interests and generated abundant opportunities for the development of micromotors and nanomotors.

12.13.1 Micromotor

Micromotors and microgenerators are power microelectromechanical systems (MEMS) for energy conversion between mechanical energy and electrical energy. With the continuous improvement of the MEMS technology, various types of compact, lightweight, and portable power conversion devices have been successfully designed and fabricated.

Nagle et al. [12.49] at MIT have presented the analysis, design, fabrication, and testing of a planar electrostatic induction micromotor. The structure and operating principle of this

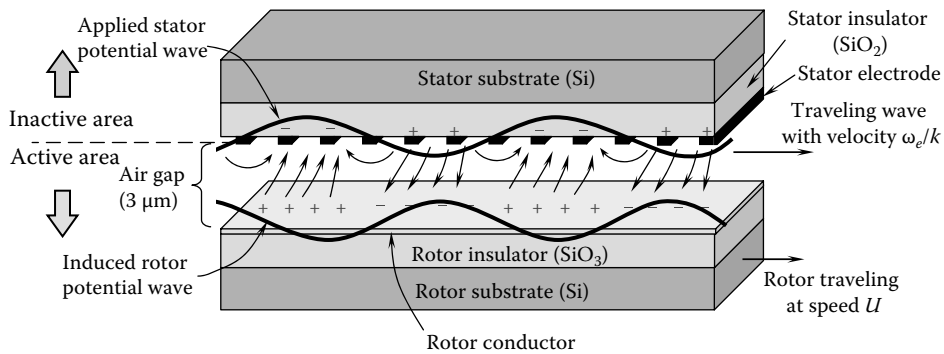
**FIGURE 12.44**

Eight-pole rotor stacks: (a) pole stack of north polarity, (b) pole stack of south polarity, and (c) spacer stack (U.S. Patent 8,264,120) [12.48]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)

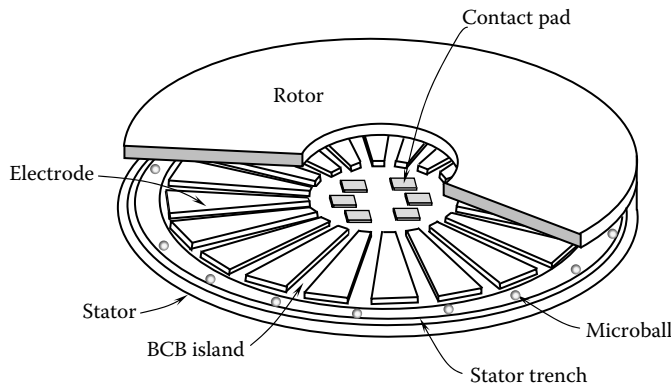
micromotor are illustrated in Figure 12.45. This is a six-phase motor with 131 pole pairs distributed on a stator. The rotor and stator are 4 mm in diameter and separated by a gap of 3 μm . The motor produces a torque of 2 $\mu\text{N}\cdot\text{m}$. The stator contains 768 radial electrodes, separated by a 4 μm space along their radial length. The electrodes are supported by an insulation layer. The rotor comprises a 0.5 μm sheet of moderately doped polysilicon deposited on a 10 μm thick oxide insulation layer that is deposited on a 400 μm thick silicon wafer. The rotor is tethered above the stator by eight silicon springs etched from the silicon wafer. During motor operation, external electronics excite the stator electrodes to produce a potential wave that travels circumferentially with a speed exceeding that of the rotor. The corresponding distribution of charges on the stator electrodes induces image charges on the rotor surface across the air gap.

This type of micromotors has the potential to perform Watt-level electrical–mechanical power conversion for applications ranging from portable electric suppliers to miniature pumps or blowers.

Ghalichechian et al. [12.50] reported the design, fabrication, and characterization of a six-phase, bottom-drive, variable-capacitance micromotor (VCM) rotary micromotor with a robust mechanical support provided by the microball bearings. Figure 12.46 shows the simplified 3D schematic of the micromotor, which is composed of three components: rotor ($\phi = 14\text{ mm}$), stator, and stainless steel microballs ($\phi = 284.5\text{ }\mu\text{m}$). Both the

**FIGURE 12.45**

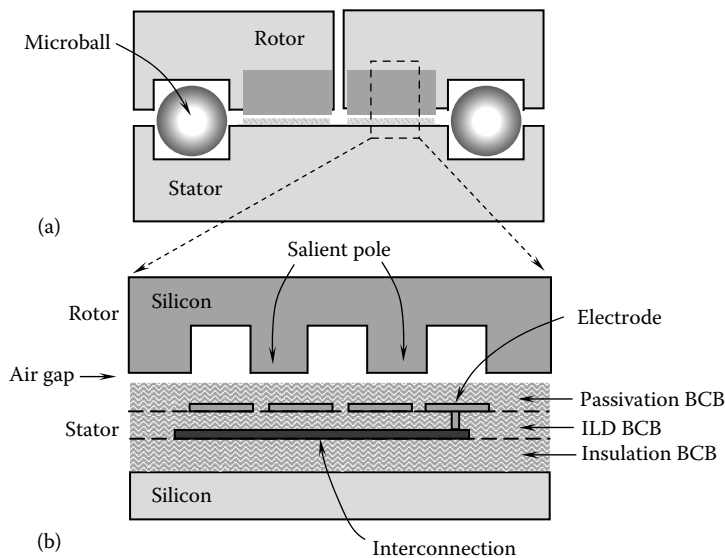
Operating principle of induction micromotor. Only the active area affects torque production because the electrode potential is enforced on the dividing plane.

**FIGURE 12.46**

Simplified 3D schematic of the rotary micromotor.

stator and the rotor are fabricated separately on silicon substrates and assembled with the microballs. Electrodes attach on the stator and salient poles are made on the rotor (Figure 12.47). When a potential is applied to an electrode, image charges are induced on an adjacent salient pole, resulting in tangential and normal forces. The tangential force is the propelling force of the rotor that aligns a rotor pole to an adjacent active electrode. The normal force assists to hold the rotor on the stator. Continuous motion of the rotor is possible by sequential excitation of the electrodes with positive square pulses in a three-phase configuration.

To analyze the effect of the air gap size on the motor torque, three different air gaps (5, 10, and 15 μm) were used in the design. As expected, the motor torque increases by more than a factor of two when the air gap is decreased from 10 to 5 μm . In contrast, the torque is reduced when the air gap is increased from 10 to 15 μm . However, fabrication of a machine with a gap of 15 μm is more feasible than 5 μm . The experimental results have shown that with the estimated air gap of 10–13 μm , the measured torque is 5.62 $\mu\text{N}\cdot\text{m}$ at the voltage of 150 V.

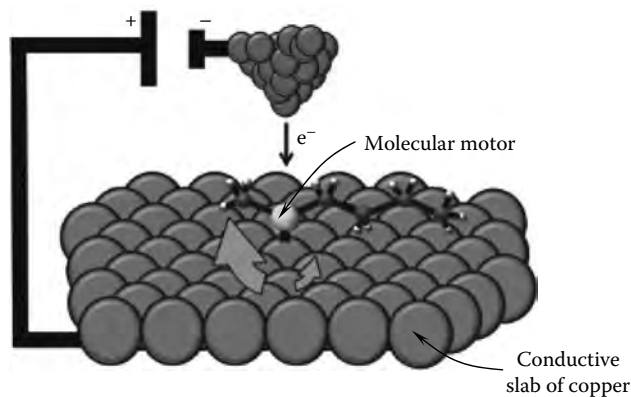
**FIGURE 12.47**

Schematic of (a) radial cross section of mechanical (bearing) and electric components of the micromotor and (b) azimuthal cross section of the stator and rotor active parts.

12.13.2 Nanomotor

The advent of the nanoscale electric motors has revolutionized the traditional concept of electric motors. In 2005, scientists at the Lawrence Berkeley National Laboratory unveiled a motor that operates by moving atoms between two molten droplets of metal. Completely contained within a carbon nanotube, the motor measures less than 200 nm across [12.51].

This record was broken by a research team of Tufts University in 2011 [12.52]. The team has developed the world's smallest motor with only one nanometer, made from a single molecule of butyl methyl sulfide on a copper surface. The molecular motor can be powered by electricity from a low-temperature scanning tunneling microscope or heat energy. As demonstrated in Figure 12.48, the molecule had a sulfur base. When placed on a conductive

**FIGURE 12.48**

The working principle of the molecular motor. (Courtesy of Sykes Laboratory, Tufts University, Medford, MA.)

slab of copper, it became anchored to the surface. The sulfur-containing molecule had carbon and hydrogen atoms radiating off to form what looks like two arms (gray). These carbon chains were free to rotate around the central sulfur–copper bond.

The spinning speed of the single-molecular motor is determined by temperature. At a temperature of 100 K (–173°C), the molecular motor spins more than a million times per second. The researchers found that reducing the temperature of the molecule to 5 K (–268°C) enabled them to precisely control the direction and rotational speed of the molecular motor, lowering the molecular motor speed to about 50 rpm. This type of motor may be used in sensing and medical test devices and nanoelectromechanical systems (NEMS). However, there is still a long way to go for practical applications of the single-molecular electric motor.

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Mechanical Design of Electric Motors

Rapid increases in energy consumption and emphasis on environmental protection have posed challenges for the motor industry, as has the design and manufacture of highly efficient, reliable, cost-effective, energy-saving, quiet, precisely controlled, and long-lasting electric motors.

Suitable for motor designers, engineers, and manufacturers, as well as maintenance personnel, undergraduate and graduate students, and academic researchers, **Mechanical Design of Electric Motors** provides in-depth knowledge of state-of-the-art design methods and developments of electric motors. From motor classification, design of motor components, model setup, and material and bearing selections to power losses, motor cooling, design integration, vibration, and acoustic noise, this comprehensive text covers the fundamentals, practical design and design-related issues, modeling and simulation, engineering analysis, manufacturing processes, testing procedures, and performance characteristics of electric motors today.

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