J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

HOMOPOLAR AND INDUCTOR MACHINES

Electric machines are energy converters in which force and torque are normally produced by a load current in the presence of a magnetic field. This article is devoted to a special class of machines in which the load winding is induced by a homopolar flux that generates dc voltage or by a flux modulation due to the variable reluctance of one member that produces ac voltage. These machines differ in construction from conventional dc and ac machines, and they are designed mostly for special applications. The following paragraphs describe the concepts of heteropolar and homopolar excitation and the derived machine concepts within the scope of this article.

Heteropolar Excitation

Rotating electrical machines are mostly heteropolar, where magnetic north and south poles are placed with alternating polarity along the circumference. In synchronous structures, the magnetic flux is supplied by one member, which is generally the rotor. In conventional dc machines which belong to the synchronous structures, the flux supplying member is the stator. Asynchronous structures, where the field generated by ac currents in the primary member is also heteropolar, are not considered here.

In machines with alternating pole polarity, the airgap field curve does not contain a homopolar component. The voltage induced in the armature winding on the other member of the machine during rotation is determined by the law of induction. Its basic integral form, valid for a conductor loop of area $\boldsymbol{A}$ with boundary line $\boldsymbol{s}$ moving with velocity $\boldsymbol{v}$ in a field with magnetic flux density $\boldsymbol{B}$, is given here:

$$u_{\rm i} = -\frac{d}{dt}\left(\iint \boldsymbol{B}\, d\boldsymbol{A}\right) + \oint (\boldsymbol{v}\times\boldsymbol{B})\, d\boldsymbol{s} \qquad (1)$$

Note that $\boldsymbol{B}$, $\boldsymbol{v}$, $\boldsymbol{A}$, and $\boldsymbol{s}$ are vectors. Applied to a coil in a machine, the first term on the right side of Eq. (1) represents the transformer voltage component due to time-variable flux, and the second term, due to the speed of the coil moving in the field, denotes the rotational voltage component. Heteropolar structures have a pole pitch defined by the field exciting member. In a dc machine where axial conductors of active length l move with constant tangential velocity $\boldsymbol{v}$ in a radial field $\boldsymbol{B}$, the voltage induced in a coil having $N_{\rm c}$ turns of 180° pitch is a well-known special case of Eq. (1):

$$u_{\rm i,c}(t) = 2N_{\rm c}l\boldsymbol{B}(x)\boldsymbol{v}$$

where

$$x = \boldsymbol{v}t \qquad (2)$$

Hence for constant speed, the ac voltage waveform reflects the flux density waveform. For sinusoidal field distribution and constant speed, the generated voltage is also a sine wave. In dc machines the alternating voltage is rectified by a mechanical commutator. In synchronous machines the no-load coil voltage follows Eq. (2) directly.

Homopolar Excitation

In contrast to the heteropolar magnetic circuit, with homopolar excitation the flux passes through the magnetic circuit in only one direction from the field-supplying member which is generally the stator. This homopolar field excitation is characteristic for two different machine types, differing in armature winding design and the voltage-induction mechanism.

In an acyclic dc machine the armature winding is fixed to the rotating member. The winding can either be a cylinder of a conducting material or consist of conductors arranged as a cage. The dc load current has to be transmitted to and from the rotor via sliding contacts. This type is called a homopolar machine in a narrower sense.

The cyclic ac machine has its armature winding placed on the stationary member together with the excitation winding. A variable reluctance rotor, which itself carries no winding, modulates the flux linked with the load winding in such a way that ac voltage induction occurs. The inductor machines are of this type. In smaller machines the homopolar flux is usually produced by permanent magnets, preferably fixed to the rotor. Such machines, known as hybrid stepping motors, are also considered in this article.

Machine Concepts

A systematic overview of the different machine concepts with homopolar and heteropolar excitation is given in Fig. 1. The following features can be assigned to the different types of machines:

- Machines with homopolar excitation

  Type (1): acyclic dc machines

  field supplied by a ring winding on the stator
  load (armature) winding in the form of a cylinder or bar-winding on the rotor, slip-ring brush contacts for current transmission

  Type (2): cyclic machines, homopolar inductor machines, and hybrid motors

  field supplied by a ring winding on the stator or by a permanent magnet, mostly on the rotor, producing an axial field
  ac armature winding on the stator

- Machines with heteropolar excitation

  Type (3): heteropolar inductor machines including medium-frequency generators

  field supplied on the stator by coils
  armature winding on the stator

  Type (4): claw-pole machines, also transversal-flux machines featuring

  field supplied on the rotor by permanent magnets with alternating polarity
  an ac ring winding with claw-pole arrangement on the stator

  or alternatively

  field supplied by a ring winding together with claw-poles on the rotor
  ac coil winding on the stator

The solutions indicated in Fig. 1 are of synchronous structure, but they do not cover conventional synchronous machines of the turbo or salient-pole type.

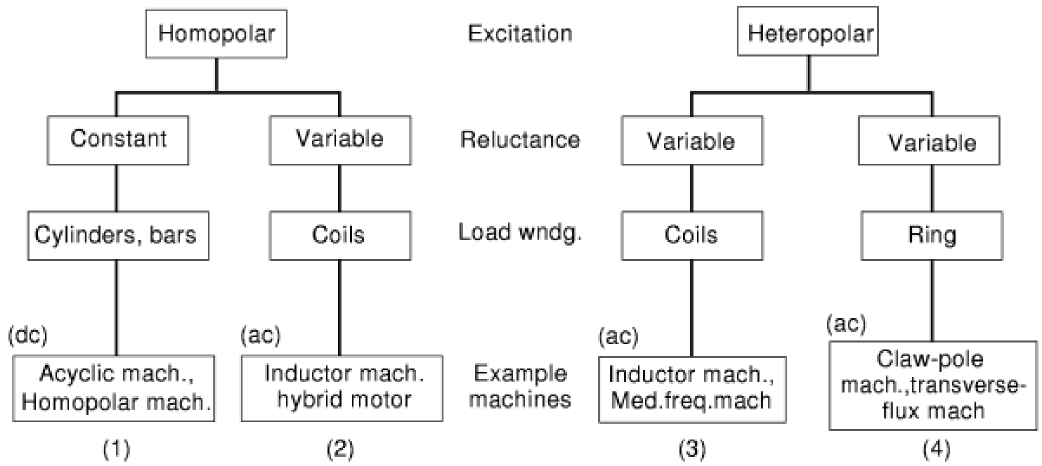

Fig. 1. Schemes of machines with homopolar and heteropolar excitation.

Although the medium-frequency generators, well known as Lorenz and Guy type machines, have lost their market to static power electronic equipment, claw-pole machines and especially transversal-flux machines are under consideration for direct-driven, low-speed generators or vehicle motors, see Ref. 17. Within the scope of this article, of the heteropolar structures only the inductor machine is considered because its behavior is similar to the homopolar inductor machine.

Machines with Homopolar Excitation

Acyclic Induction. The mechanism of voltage induction in a homopolar acyclic machine is not easily understood. It was shown that an exact theory requires a relativistic approach. However, for a practical understanding, the following description may be sufficient (see Fig. 2). A conductor cylinder 1 of length l is connected to slip rings 2 and 2′ with brushes 3 and 3′ gliding on them. They supply the load 4. The induced voltage $u = -d\Psi/dt$ in this circuit is given by the rate of change of the flux linked with area $\boldsymbol{A}$. The boundary of $\boldsymbol{A}$ represents one turn, and the flux linkage is equal to the flux, $\Psi = \Phi = \boldsymbol{B} \cdot \boldsymbol{A}$. Because the flux density is constant, $u = -\boldsymbol{B} \cdot d\boldsymbol{A}/dt$. There is only one portion of $\boldsymbol{A}$ which changes due to rotation. When the rotor surface speed is $\boldsymbol{v}$, the winding area decreases so that $d\boldsymbol{A}/dt = -l\boldsymbol{v}$, and we end up with:

$$u_i = l\boldsymbol{B}\boldsymbol{v} \qquad (3)$$

This equation is formally the same as for one armature conductor of a conventional dc machine; see also Eq. (2). Here with constant flux density and speed the equation describes a dc voltage. The inherent absence of voltage harmonics is the reason that homopolar acyclic machines are recommended as tacho generators.

Cyclic Induction. For the cyclic types of machine, consider Fig. 3. Both excitation 1 and armature winding 2 are placed on the same stationary member. The rotor has a salient structure. The homopolar flux passes from stator to rotor in the left part I and from rotor to stator in the right part II. The pole pitch of the ac winding is related to the number of rotor teeth. Depending on the rotor position, the flux linkage of a coil varies between a maximum and a minimum value. Suppose the variable reluctance has only a fundamental

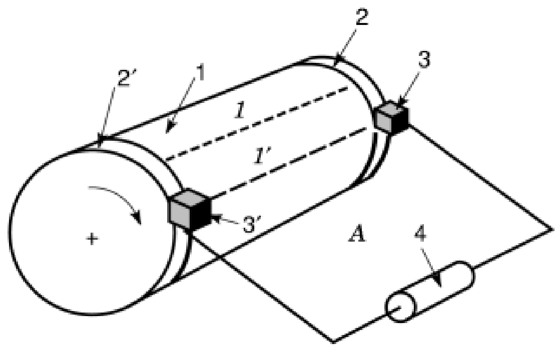

Fig. 2. Illustration of homopolar acyclic induction.

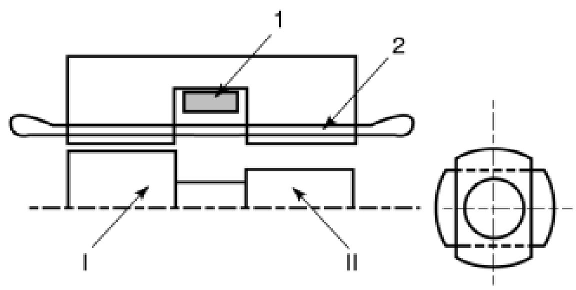

Fig. 3. Principle construction of a homopolar ac machine.

component. Then we can describe the flux (Fig. 4) by

$$
\begin{aligned}
\Phi_0 &= (\Phi_{max} + \Phi_{min})/2 \\
\Phi_d &= (\Phi_{max} - \Phi_{min})/2 \\
\Phi_I &= \Phi_0 + \Phi_d \cdot \cos\alpha \\
\Phi_{II} &= -\Phi_0 + \Phi_d \cdot \cos\alpha \\
\Phi_a &= \Phi_I + \Phi_{II} = 2\Phi_d \cdot \cos\alpha
\end{aligned}
\tag{4}
$$

Φ_0 is the mean value, and Φ_a the resulting flux component linked with the ac winding coil. When a machine that has z_r rotor projections rotates with constant angular speed Ω, the induced voltage in a coil of N_c turns is given by

$$u_{i,c}(t) = 2N_c\Phi_d \cdot \sin(z_r \cdot \Omega t) \tag{5}$$

These machines utilize only up to half of the power per volume compared with heteropolar machines because twice the amplitude of the ac flux density component cannot exceed the homopolar flux density.

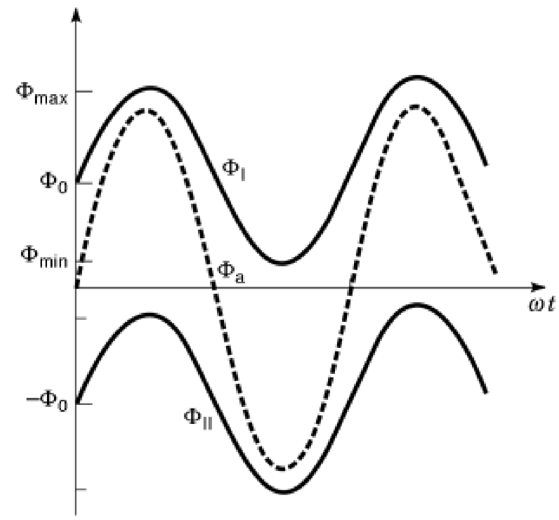

Fig. 4. Flux waveform of a homopolar ac machine.

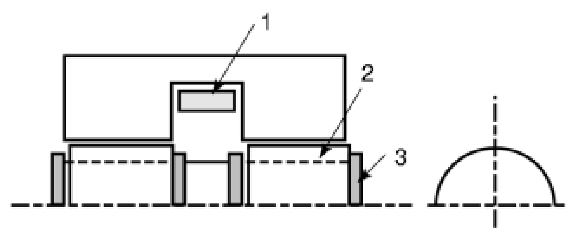

Fig. 5. Principle construction of a homopolar dc machine.

Homopolar DC Machines

Designs and Construction. For the principle of the classical homopolar dc machine, see Fig. 5. Generally the machine is designed as a double system to obtain symmetrical conditions for flux and armature reaction. It consists of a stationary member with an excitation winding 1 and a rotating member carrying the armature 2, here, in two parts. In its simplest form the winding consists of a conducting cylinder. Slip rings 3 at both ends of the conductors on which brushes are gliding transmit the load current.

This machine is typical for very low voltages of only a few volts. A series connection of conductors cannot be made in a simple way. On the other hand, the ability to supply very large currents drew attention to homopolar generators for special purposes. However, static equipment with power electronic circuits has become a serious competition, so homopolar generators have had no breakthrough for electrolytic plants.

However, homopolar dc machines received new consideration some years ago for supplying impulse loads, such as in electromagnetic launch facilities (rail guns) or nuclear fusion (tokomacs). The concept is to couple the homopolar generator with rotating energy storage (flywheel). Designs for rated values of up to 12.5 MA, 50 V impulse loads with 1 GJ energy have been reported. See also references 1,2,3.

The construction can have an iron or a non-iron core. Especially for the latter, construction with a superconducting excitation winding offers advantages. In the 1970s a homopolar disk machine, developed in the U.K. and intended for application in marine propulsion, drew much attention. A special feature was the

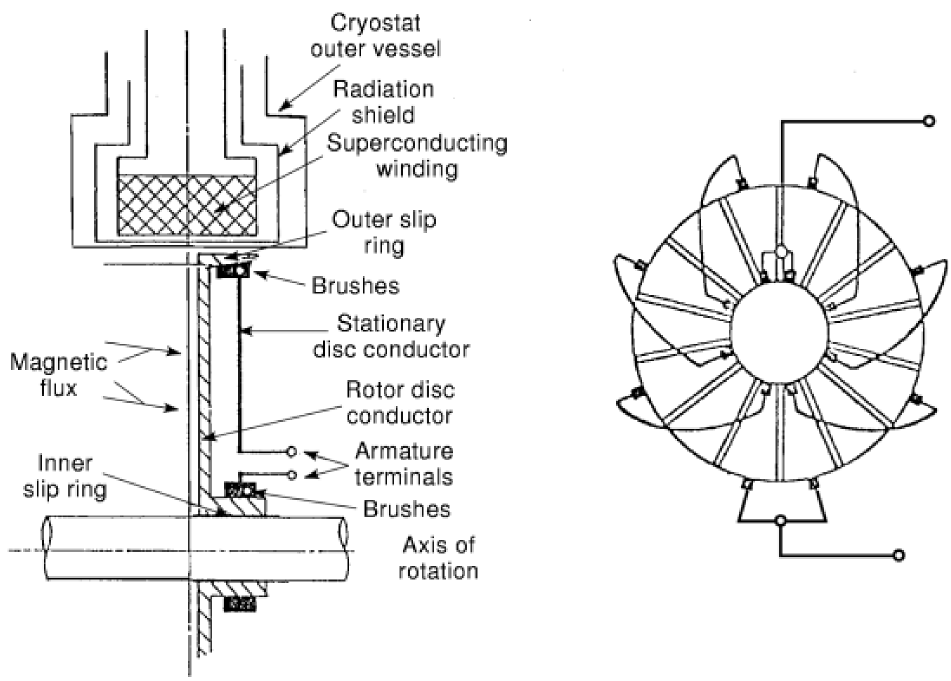

Fig. 6. Homopolar dc generator with segmented armature disc and superconducting excitation winding.

segmentation of the armature disk, allowing series connection of conductors to obtain higher voltage values with the penalty of additional brushes (Fig. 6). See also references 4,5,6.

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Current Transport by Sliding Contacts. A problem known from synchronous generators of high rating is the transport of very large currents by slip rings and brushes. This topic has also drawn attention in connection with the development of homopolar dc machines for current of more than 2 kA where problems with brush wear are encountered with solid material combination, and, moreover, where the voltage drop is unfavorably high compared to the machine armature voltage.

Normal sliding contacts combine for example, bronze rings with carbon brushes. Selecting the material combination and design features, like surface finish and specific contact pressure, requires much experience to obtain an operating life of more than several thousand hours.

For very large current in connection with large gliding speeds, new concepts, such as metal matrix contact surfaces and fluid contacts have been investigated. In the first concept wear-resistant materials are combined with conductive binders. Good results have been reported with an aluminum bronze matrix. Liquid contacts were first investigated in Austria in the 1960s using mercury together with different contact arrangements. It was shown that currents of a few thousand amperes can be transferred with only a small voltage drop (Fig. 7). Due to the toxic properties of Hg, the environmental impact and safety requirements make this solution expensive for practical use. Contacts using NaKa have been considered as an alternative. See also Refs. 7 and 8.

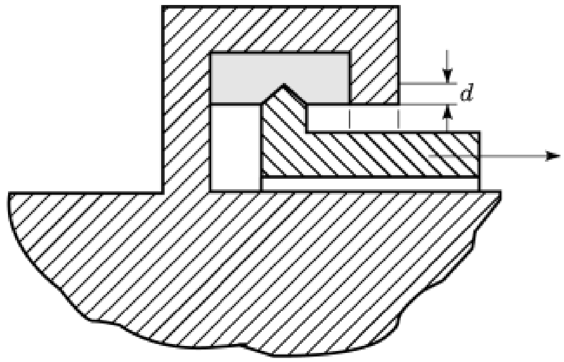


Fig. 7. Principal arrangement with liquid ring contact.

Inductor Machines

Designs and Construction. An inductor machine is a synchronous machine in which one member, usually stationary, carries armature and excitation windings or permanent magnets suitably disposed relative to each other, and in which the other member, usually rotating, is without windings but carries a number of regular projections.

In the group of homopolar machines the field winding excites a unipolar flux which is modulated by rotor teeth to produce an alternating flux linkage of the ac winding. Variable reluctance is essential for their performance.

There are both ac windings and dc excitation windings on the stator. In such machines the stator flux is unipolar with an alternating component superimposed on the dc excitation field. Hence the useful amplitude of the alternating flux component is limited to less than half the maximum instantaneous flux.

There are two different embodiments of inductor machines. In the configuration of Fig. 3 the rotor flux has a unipolar direction. This design is the homopolar inductor machine, similar to hybrid step motors in the fractional horsepower range. In the version of Fig. 8, the rotor teeth flux alternates, and this type is a heteropolar inductor machine.

Operation. Inductor machines are of the synchronous type. This applies to the arrangements outlined in Figs. 3 and 8. For the latter, the operation is illustrated by Fig. 9. The ratio of rotor teeth z_r/stator pole pairs p_s is an uneven number. Here we have $z_r = 6$ and $p_s = 2$. The ac winding normally comprises $m = 3$ phases. Then the coil pitch is one-half of the rotor tooth pitch. The phases U, V, W, and the field winding F are magnetically coupled. A damper winding can be introduced if required.

The properties of such a machine can be described analogously to a synchronous machine using the well-known equations and circuit representations according to Park's theory. The variable reluctance is described by

$$\lambda_0 = \frac{\lambda_{max} + \lambda_{min}}{2}$$

and

$$\gamma = \frac{\lambda_{max} - \lambda_{min}}{2\lambda_0} \qquad (6)$$

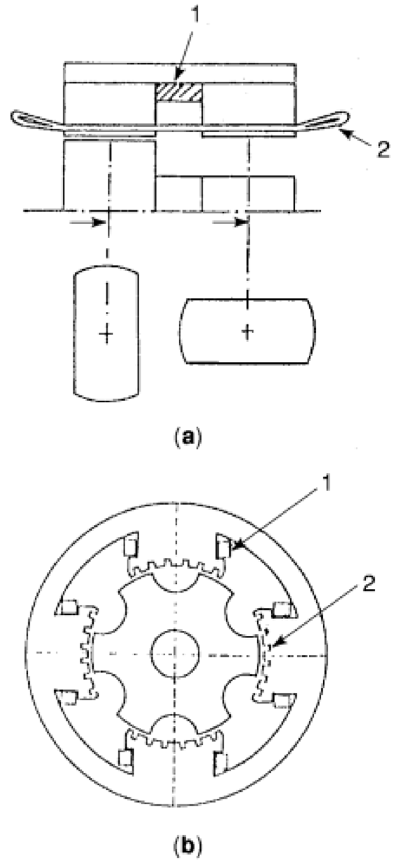


Fig. 8. Versions of an inductor machine: (a) homopolar; (b) heteropolar.

where λ_0 is the average specific magnetic permeance of the air gap and γ is the modulation factor.

Because the period of λ is the rotor tooth pitch, it consists only of uneven components. Note that in Eq. (4) field harmonics above the fundamental were neglected. Then the machine model is similar to a conventional turbo rotor synchronous machine, except that the armature reaction needs special consideration when describing the mutual inductance of the field and the ac winding. The direct and quadrature axis (d,q)-components of the armature flux are given in terms of the armature current d,q-components and the field current by

$$\begin{aligned}\psi_\mathrm{d} &= \gamma L_\mathrm{m} \cdot i'_\mathrm{f} + L_\mathrm{m} \cdot i_\mathrm{d} \\ \psi_\mathrm{q} &= L_\mathrm{m} \cdot i_\mathrm{q}\end{aligned} \tag{7}$$

where L_m is the phase inductance corresponding to the average magnetic permeance.

The relevant reactance $X_\mathrm{m} = \omega L_\mathrm{m}$ consists of two parts. One represents the magnetizing component $X_{\mathrm{m}\mu}$, and the rest X_ms has the character of a stray field component. This is described by

$$X_\mathrm{m} = X_{\mathrm{m}\mu} + X_\mathrm{ms} = \frac{\gamma^2}{2} X_\mathrm{m} + \left[1 - \frac{\gamma^2}{2}\right] X_\mathrm{m} \tag{8}$$

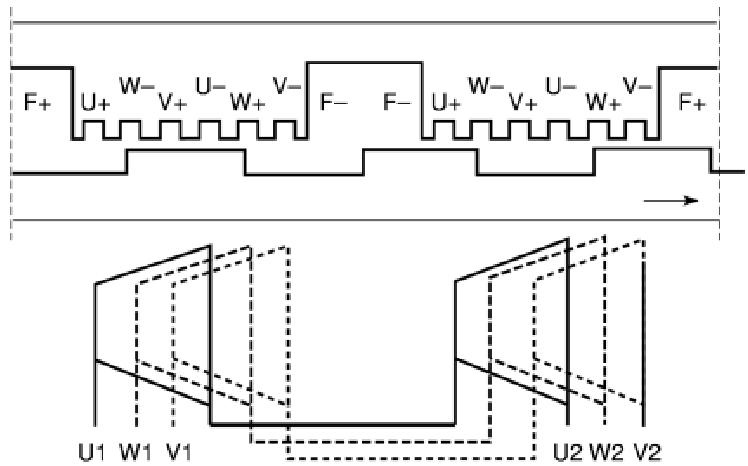


Fig. 9. Arrangement of poles and winding coils in a heteropolar inductor machine.

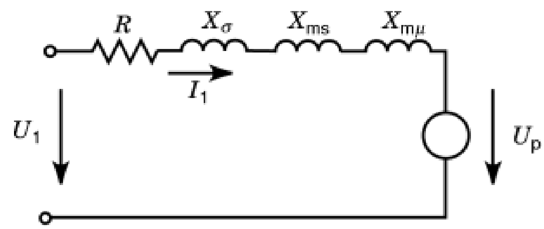


Fig. 10. Circuit diagram of inductor machine to describe ac operation.

So the ac circuit representation of the machine in two-axis components without damper winding can be described by Fig. 10, where $U_p = \gamma X_m \cdot i'_f$ is the equivalent no-load voltage, and X_σ is the conventional stray reactance comprising slot-, overhang- and tooth-tip stray field components. Although γ is not very different from 1, $X_{ms} \approx 0.5\, X_m$. The short-circuit reactance of the inductor machine cannot be made significantly lower than the synchronous reactance. The values reported in Ref. 9 for a 62 kVA, 3000 rpm machine were, in the per-unit system, $X_d = 0.59$, $X'_d = 0.42$, and $X''_d = 0.39$ p.u.

Variable-Speed Inductor Machine Drive

Inverter with dc Side Commutation. An adjustable speed drive for large power ratings is a load-commutated inverter (*LCI*) synchronous motor drive having a dc link converter. Because of the load-commutated operation of the machine-side thyristor inverter, the subtransient inductance of the machine is part of the commutation circuit, limiting the firing angle, and hence the maximum speed and power factor of the machine. This is why machines with small stray inductance values are preferred.

Some years ago a new type of inverter with backward conducting valves in the form of thyristors with parallel diodes in the reverse direction was proposed. This inverter operates with external commutation on the dc side, and the machine inductance is no longer a part of the commutation circuit (Ref. 10). This draws attention to such types of synchronous motors which, because of their design, are suited for high speeds but have large stray inductances. Among them are homopolar and claw-pole type machines. In the following the

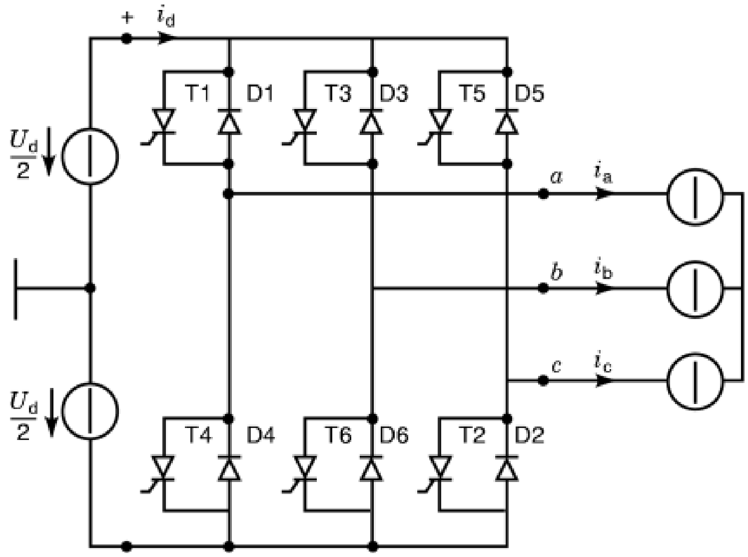


Fig. 11. Six-pulse bridge converter with dc side commutation.

steady-state operation of an inductor motor supplied by a six-pulse bridge inverter of the dc side commutated type (*DCI*) is investigated and compared with a motor of standard design in a conventional LCI drive.

The inverter considered is characterized by external commutation on the dc side. The circuit of Fig. 11 contains thyristors and parallel diodes in reverse direction in each of the six branches. These bidirectional valves determine the properties of the inverter which in this article will be called DCI. Compared with the common LCI bridge circuit with unidirectional thyristor switches, we can recognize dual behavior. The latter is best understood by assuming an alternating fundamental voltage on the ac side and constant current on the dc side, while the new converter reveals its basic performance when there is a fundamental ac current source on the ac side and a constant dc voltage impressed on the dc side.

Under these assumptions Fig. 12 shows the waveforms of phase voltage and current on the ac side when the control angle $\alpha = 150^\circ$ and the energy flows from the intermediate circuit to the ac load. In the absence of an overlap, the fundamental power factor cos ϕ is determined by $\phi = \pi - \alpha$. We can conclude that to attain a good power factor, the control angle α should be as close as possible to 180°. Except for the hold-off interval assigned to the thyristors, α is limited only by the inductance in the dc commutation circuit which is very small. Hence the overlap angle is almost negligible. This is different in the conventional LCI inverter where considerable values of the overlap angle appear. Figure 13 allows a comparison.

Performance. In this section the steady-state operation of a converter drive with an inductor type machine is investigated. The complete power circuit diagram comprises a controlled six-pulse rectifier supplied by the utility system, an intermediate circuit with a capacitor acting as a voltage source, the dc side commutated inverter, and the synchronous motor.

As an example a 12-pole motor is considered with a rated speed of 3000 min^{-1} assigned to 300 Hz (Ref. 11). It is characterized by a relatively small synchronous reactance and relatively large subtransient and short-circuit reactance values ($X_d = 0.59$, $X'_d = 0.42$, $X''_d = 0.39$, and $X_k = 0.47$ p.u.).

The steady state of a converter drive with an inductor motor is simulated. The motor is operated under rated load in an overexcited state. This means that the armature current is ahead of the terminal voltage. Integration by the Runge–Kutta method was used to obtain high accuracy. In Fig. 13 simulation results are presented for the motor running at rated speed with rated power supplied by the inverter with commutation

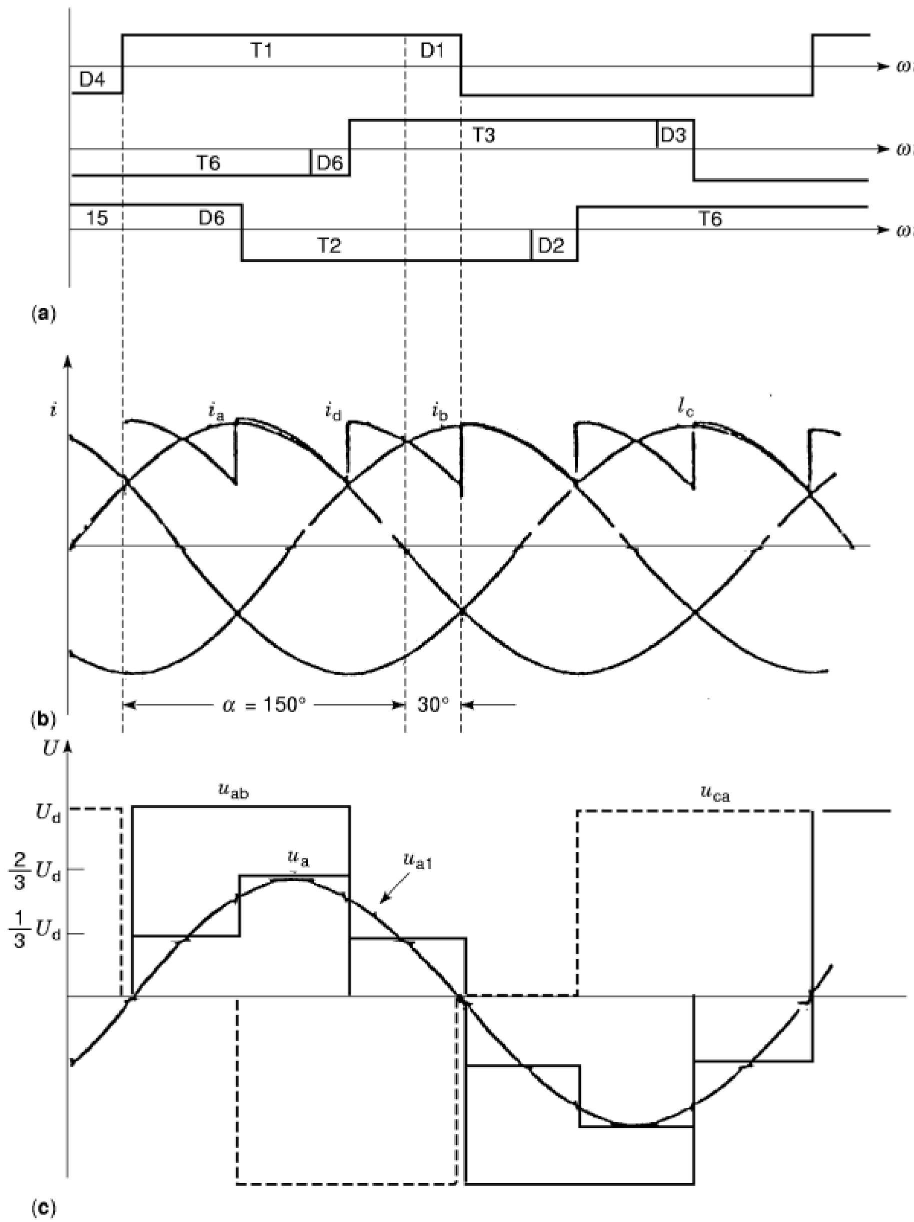


Fig. 12. Idealized voltage and current waveforms of the dc side commutated inverter (*DCI*).

on the dc side. The firing angle was $\alpha = 143.4^\circ$. The overlap of $u = 0.4^\circ$ was almost negligible. This results in a margin angle of $\gamma = 37^\circ$ with an equivalent of 342 μs for the thyristors to recover. Under these circumstances the fundamental power factor cos $\phi = 0.8$.

For comparison, a standard salient-pole synchronous motor supplied by a conventional LCI inverter was considered. Its subtransient reactance was $X''_d = 0.15$, the transient reactance was $X'_d = 0.25$, and the

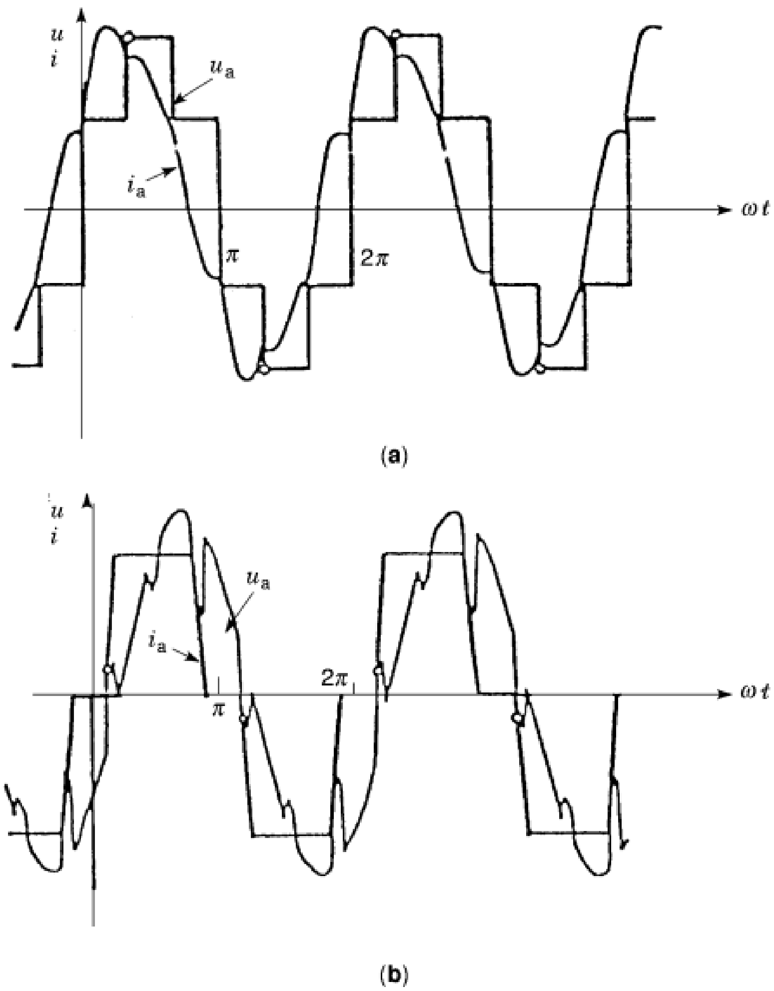


Fig. 13. Comparison of motor voltages and currents (a) for dc side commutated inverter (*DCI*); (b) for load-commutated inverter (*LCI*).

synchronous reactance was $X_d = 0.9$ p.u. The firing angle was adjusted to yield the same power factor cos $\phi = 0.8$.

The analysis of the harmonic contents of machine current and terminal voltages shows remarkable differences between the LCI and the DCI performance. In Table 1 the fifth- and seventh-order harmonics reveal only a remarkably small deviation from a sinusoidal shape with the DCI. Consequently, the pulsating torque component generated by a DCI drive is also smaller than with a LCI configuration.

A deeper insight into the characteristics of the converter fed machine can be obtained by inspecting the trajectories of voltages and current in the space-phasor plane. It is well known that the steady-state, 120° block output waveform of a three-phase, six-step inverter is associated with a regular hexagon in the phase plane. Its corners correspond to discrete values of the space phasor during one-sixth of the period.

In Fig. 14 trajectories are plotted with respect to the stator reference frame. With the DCI the voltage trajectory forms a hexagon. The current trace indicates the presence of some harmonics. In the case of a purely sinusoidal waveform, there would be a circle. Note that the angular velocity of the space phasor is not

Table 1. Harmonic Contents in DCI and LCI Output (per unit)

Component	DCI	LCI
U5	0.200	0.120
U7	0.143	0.128
I5	0.094	0.189
I7	0.057	0.128

constant (parameter values of synchronous angle ωt are not indicated here). It is interesting to consider the phase diagrams of the same quantities when the reference frame rotates with synchronous speed, as shown in the lower part of Fig. 14. Now deviations from a sinusoidal waveform are indicated by a loop around the fundamental phasor.

To make a comparison with the performance of the conventional LCI, refer to Fig. 15. According to the dual behavior, the hexagon here represents the nearly 120° block waveform current. The motor terminal voltage resembles a circle except for the notches due to commutation.

The aforementioned converter drive is suitable for high speeds. It is similar to the load-commutated inverter (*LCI*) drive with a synchronous motor but features a voltage source link and an inverter with dc side commutation (*DCI*). This inverter matches favorably with machines which, because of their design, have a large short-circuit inductance. Among these are machines of the inductor type with their excitation winding on the stator. The inverter circuit is simple because normal thyristors for line commutation are used and it does not need switch-off semiconductor elements like gate-turn-off thyristors (GTOs). This simplicity may compensate for the lower rating of inductor machines as compared with standard design synchronous machines.

Hybrid Stepping Motors

Designs and Construction.

Stepping motors are known in different configurations:

- Permanent magnet motors with heteropolar excitation, especially claw-pole motors
- Variable reluctance motors, with double-salient structure
- Hybrid motors with one permanent magnet combined with double-salient structure

Of these types the hybrid motor allows for small step angles and displays large holding torques. Hence it is preferred for industrial applications. Figure 16a shows the principle of construction. Note that the cogged rotor disks embracing the axially magnetized permanent magnet are displaced by one-half of the tooth pitch. The step angle is given by

$$\alpha = \frac{2\pi}{2mz_{\mathrm{r}}} \cong \frac{360^\circ}{2mz_{\mathrm{r}}}$$

The relatively simple motor depicted in Fig. 16(b) has $m = 2$ phases and $z_{\mathrm{r}} = 9$ rotor teeth. Hence $\alpha = 10^\circ$. Phase numbers up to $m = 5$ are in use.

Because a hybrid motor is also a synchronous machine, the relevant analysis can be adapted. Assuming a two-phase symmetrical system at constant synchronous speed with sinusoidal waveforms of voltages and

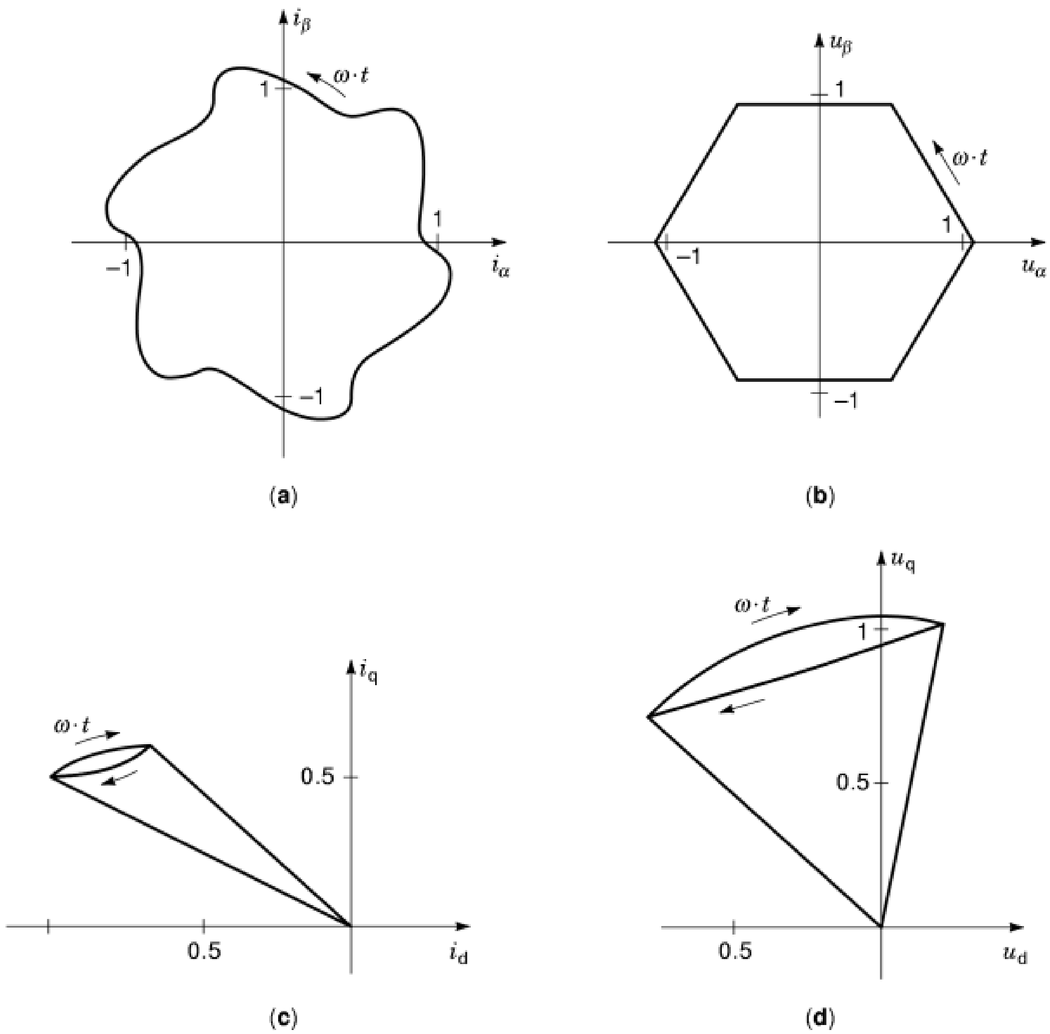


Fig. 14. Space phasor trajectories for steady-state operation of a DCI: (a,b) in stator frame; (c,d) in synchronous rotating frame.

currents, the voltage equations in d,q-components can be written as

$$\begin{bmatrix} i_\mathrm{d} \\ i_\mathrm{q} \end{bmatrix} = \frac{1}{R}\frac{1}{1+(\omega\tau)^2(1-q^2)}\begin{bmatrix} 1 & \omega\tau(1-q) \\ \omega\tau(1+q) & 1 \end{bmatrix} \begin{bmatrix} \hat{U}_\mathrm{s}\sin\vartheta \\ \hat{U}_\mathrm{s}\cos\vartheta - \omega\Psi_0 \end{bmatrix} \tag{9}$$

where

$\tau = L/R$ is the winding time constant with $L = (L_d + L_q)/2$
$q = (L_d - L_q)/(L_d + L_q)$ is the reluctance factor
$\omega = z_\mathrm{r} \cdot d\alpha/dt$ is the motor speed in electrical rad/s

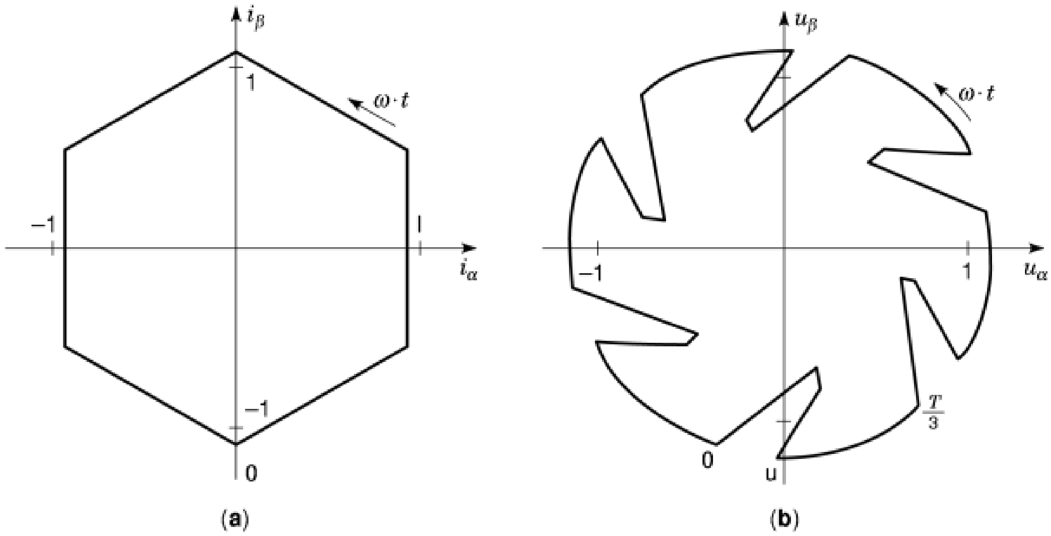


Fig. 15. Space phasor trajectories for steady-state operation of a LCI: (a,b) in stator frame.

ϑ = is the load angle
Ψ_0 = is the flux linkage due to permanent magnet excitation
$\hat{U}_s$ = is the amplitude of a sinusoidal terminal voltage of frequency ω

In Fig. 17 the circuit representation in d,q-quantities is depicted. The torque is made up of two components, one dependent on the magnet flux and the other on the reluctance modulation factor. This is illustrated by the torque equation

$$T = i_q \Psi_0 + (L_d - L_q) \cdot i_d i_q \tag{10}$$

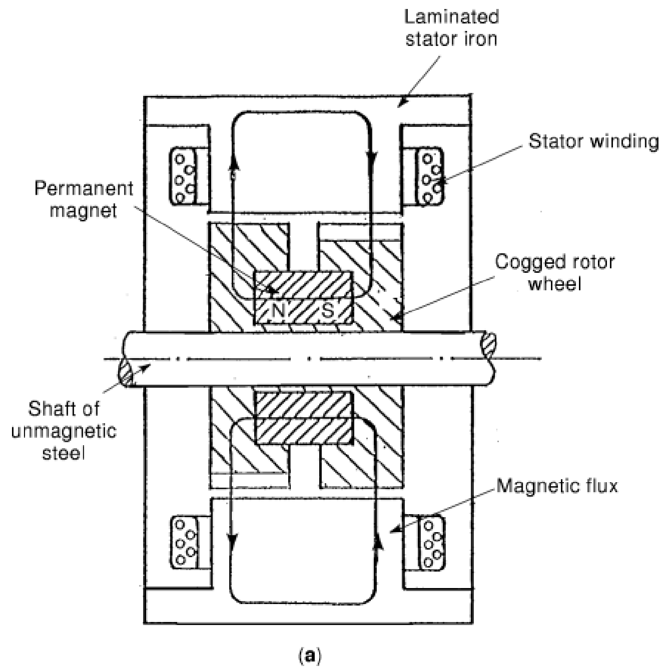
This model does not take into account iron losses due to alternating magnetization. It needs the addition of damper windings to describe the motor behavior in constant current operation.

Stepping motors are electromagnetic energy converters that render a certain angle increment on the application of one impulse. The number of steps which the rotor proceeds in 1 s corresponds to the step frequency f_z. Two-phase motors can be supplied in full-step or half-step operation (Fig. 18).

In practice the maximum torque decreases with increasing step frequency. It is usual to specify the performance of a motor by three limiting torque curves which imply synchronous operation on a sinusoidal supply (see Fig. 19):

(1) maximum torque for continuous operation assuming constant speed
(2) maximum load torque for starting (no additional inertia)
(3) maximum load torque T_L for starting with a load inertia J_L

The transient behavior can be investigated by determining the trajectory of speed versus position in the phase plane. Successful operation following a set-point sequence is indicated by a stable end position, after decay of oscillations, with the proper number of steps accomplished (Fig. 20).



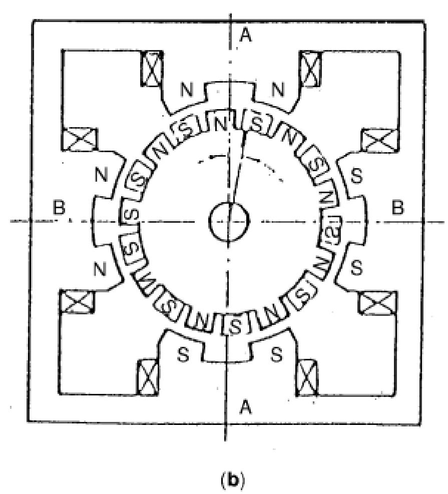


Fig. 16. Principle construction of two-phase hybrid motors: (a) section; (b) example with 10° step angle.

Stepping Motor Drives. The transistor switches energizing the windings can be arranged in bipolar or unipolar circuits. The latter require splitting up the phase windings into two coils each, but need only half the number of switches compared with the bipolar circuit. Hence the unipolar version prevails.

Manufacturers offer a variety of supply equipment, frequency generators, and program units. With suitable motors, subdivision of the step number per turn can be made in the so-called microstep scheme. For

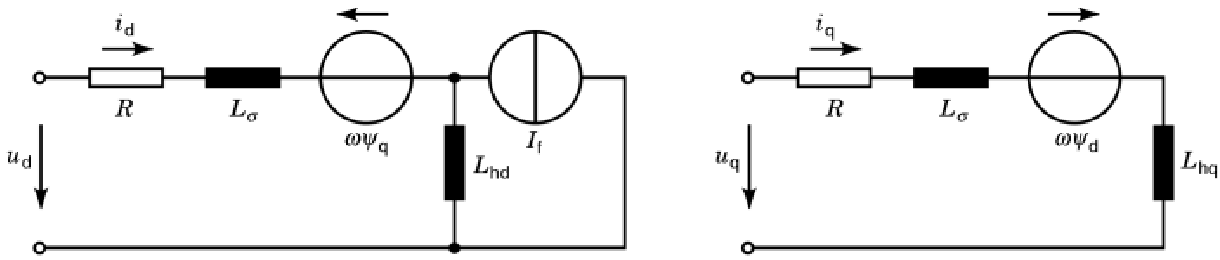


Fig. 17. Circuit representation of a hybrid motor in d,q-components.

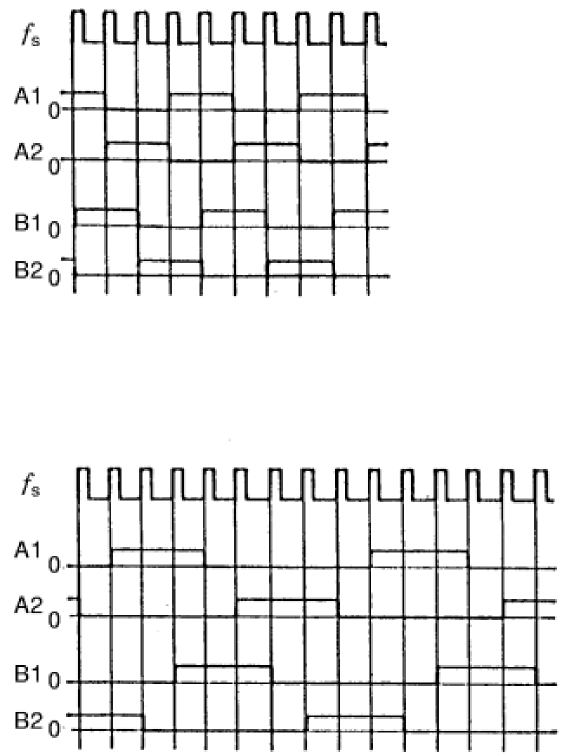


Fig. 18. Step rate and excitation pattern for two-phase, full-step and half-step operation.

instance a 200 step (1.8°) motor can be run with five intermediate positions per full step by controlling the phase currents with a supplementary unit.

The standard operation of stepping motors is in open-loop control. When loaded above the maximum available torque, the motor loses steps. In recent times strategies for a closed-loop operation have been introduced by which the performance is made similar to an electronically commutated (*EC*) motor and the main disadvantage of stepping motors is overcome. This is especially true when available methods for sensorless angle determination are applied.

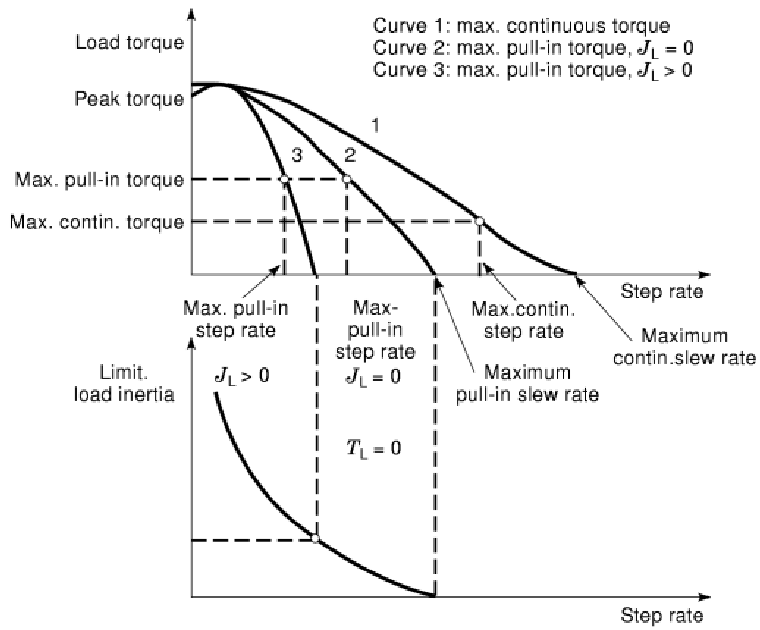


Fig. 19. Torque limits in dependence on step rate.

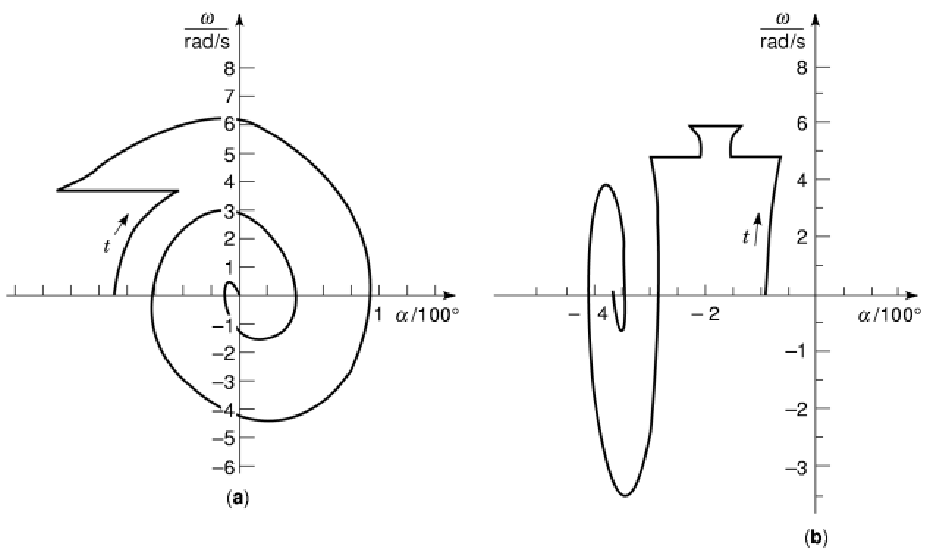


Fig. 20. Phase-plane representation (angular speed over angle) of a sequence of steps: (a) two steps; (b) four steps with step loss.

Appendix

Definitions from the International Electrotechnical Vocabulary

Homopolar Machine A machine in which the magnetic flux passes in the same direction from one member to the other over the whole of a single air-gap area (411-31-02)

Acyclic Machine A direct current homopolar machine (411-31-03)

Heteropolar Machine A machine having successive physical or effective poles of opposite polarity (411-31-04)

Inductor Machine A synchronous machine in which one member, usually stationary, carries armature and excitation windings or permanent magnets effectively disposed relative to each other, and in which the other member, usually rotating, is without windings but carries a number of regular projections (411-31-11)

BIBLIOGRAPHY

1. G. Wenqi *et al.*, Development and test of a 300 kW superconducting homopolar generator, *IEEE Trans. Magn.*, **32** (4): part 1, 2280–2283, 1996.
2. G. Wenqi, T. Shaodong, Superconducting homopolar machine, *13th Int. Cryogenic Eng. Conf.*, 1990, Beijing, China, *Cryogenics*, **30**: p. 743.
3. R. C. Zowarka, J. P. Kajs, 25 GW homopolar generator experiment, *8th IEEE Int. Pulsed Power Conf.*, San Diego, 1991, pp. 263–267.
4. C. J. Mole *et al.*, Superconducting electrical machinery, *Proc. IEEE*, **61**: 95–105, 1973.
5. M. Hippner *et al.*, High speed homopolar synchronous generator no load calculations with the help of a finite element package, *Int. Conf. SM'100*, ETH Zurich, 1991, pp. 812–816.
6. A. J. Micham *et al.*, The self-excited homopolar generator, part 1: Theory and electrical design, *IEEE Trans. Magn.*, **25**: 362–368, 1989.
7. F. Caricchi, New mercury-gap ring-collector system for double-armature generator, *IEEE Trans. Ind. Appl.*, **29**: 1129–1134, 1993.
8. D. Maribo, N. A. Sondergaard, Further studies of a low melting point alloy used in a liquid metal current collector, *IEEE Trans. Compon. Hybrids Manuf. Technol.*, **CHMT-10**: 452–455, 1987.
9. W. Bedorf, *Ermittlung der feldverteilung und berechnungsmethoden fuer induktormaschinen im hinblick auf die anwendung als stromrichtermotor*, Ph.D. Dissertation, RWTH, Aachen, 1977.
10. H. P. Beck, M. Michel, Die sechspulsbrueckenschaltung mit gleichspannungsseitiger kommutierung, *Arch. Elektrot.*, **66**: 49–56, 1983.
11. M. Stiebler, G. Kezhong, Homopolar synchronous machines for converter fed drives, *Proc. Int. Conf. Evolution and Modern Aspects of Synchronous Machines*, part 3, Zuerich, 1991, pp. 848–851.
12. H. Sequenz, *Elektrische Maschinen*, 8th ed., Wien: Springer-Verlag, 1971.
13. A. D. Appleton, Performance of a large superconducting motor, *Proc. 3rd Int. Cryogenic Eng. Conf.*, Berlin, 1970, pp. 443–446.
14. J. He, F. Lin, A high frequency high power IGBT inverter drive for 45 HP/16,000 rpm brushless homopolar inductor motor, *IEEE Ind. Appl. Conf.*, Orlando, 1995, pp. 9–15.
15. T. Kenyo, *Stepping Motors and Their Microprocessor Controls*, 2nd ed., Oxford: Clarendon Press, 1994.
16. M. Jufer, G. Heine, Hybrid stepping motors-25 years of development, *Proc. 25th Annu. Symp. Incremental Motion Control Syst. Soc.*, San Jose, 1996, pp. 307–316.
17. H. Weh, Transverse flux machines in drive and generator applications, *Stockholm Power Tech*, Stockholm, June 1995.
18. IEC 60050-411:1996 International Electrotechnical Vocabulary, Chapter 411 Rotating Machines.

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