Electrical Motors/Generator Technology

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1.0 INTRODUCTION

Devices, transforming energy by electromagnetic processes are understood as electrical machines. There are three types of devices for energy conversion that can be distinguished:

- *Transformers* are converters transforming electrical energy into another form of electrical energy with different properties (voltage, current);
- *Motors* where the electrical energy is converted into mechanical energy; and
- *Generators* for generating electrical energy from mechanical energy.

Motors and generators are in fact the same devices as electromagnetic-electromechanical energy conversion is *reversible*. So when a motor brakes, it will reverse the power consumption and try to put power back into the supply.

The vast majority of electrical machines uses *magnetic force* principles to achieve the conversion. Electrical forces, based upon the attraction of charges, are in general too weak for practical applications and are only used in (silicon) micromachines or microphones.

Magnetic forces arise due to the minimization of magnetic field energy. For instance, when a permanent magnet is close to a piece of ferromagnetic iron, it is attracted as the field energy is minimized when the air gap between the two pieces is as small as possible. In fact this sort of force, called *reluctance*[1] *force*, is induced in movable or deformable structures by a single magnetic field until a minimum of field energy is attained. This force causes all sorts of attraction and alignment, for instance in machines with (magnetic) asymmetrical shapes.

[1] Reluctance is to be understood as a magnetic equivalent to resistance (to magnetic flux instead of electrical current).

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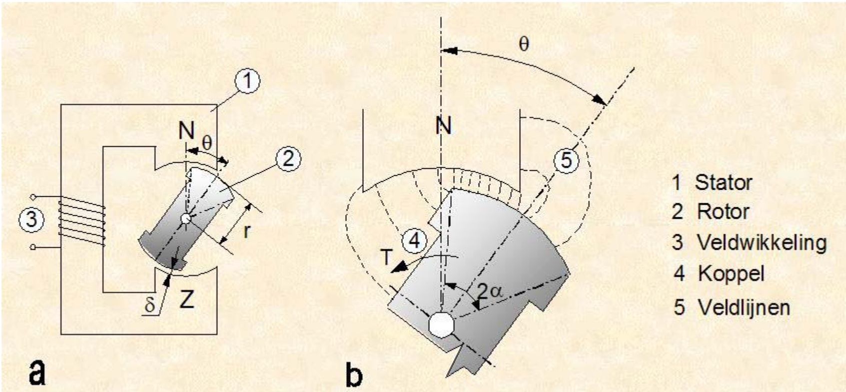


Figure 1.1: The Reluctance Torque (4) Aligns the Rotor (2).

However, the best known magnetic force is the force on a current carrying conductor in a magnetic field, the *Lorentz force*: the force is proportional to the magnetic induction of the field, the current in the wire and the length of the wire:

$$F = B \cdot \ell \cdot I \qquad (1.1)$$

This is in fact a equivalent to field-energy minimization application as the current in the wire causes a concentric magnetic field around it and the total magnetic field is minimized by 'pushing this out'. Such a field minimization by interaction of two (independent) magnetic fields, causing powerful forces and torques, is used in most electrical machines, as it is in general more powerful than the reluctance force, but the current involved causes Joule losses.

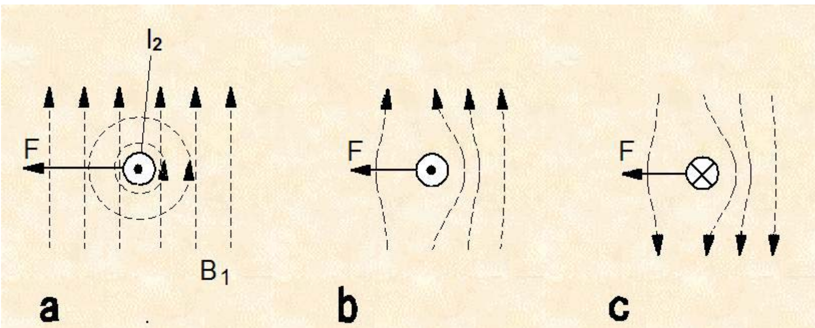


Figure 1.2: Lorentz Force Principle:
(a) superimposed magnetic field, (b-c) force minimizing field energy.

In the following sections the basic concepts and principles of the most important electrical motors/ generators are introduced. Their function and fundamental operational behaviour will be discussed.

2.0 DC MACHINE

The DC machine can operate as either a generator or motor. Its use as a generator is limited to small units, e.g. the bicycle lighting dynamo, and special generator applications. The DC motors can still be found in various applications, such as machine tools (drills), printing presses, fans, pumps, cranes, textile mills, etc. However, it must be noted that due to several reasons: decreasing costs for power electronic control circuits and the less expensive purchase and maintenance cost of induction machines, the DC machine is more and more vanishing from the market. Approximately 95% of all current electrical motors are variable-speed induction motors. Nevertheless, it is included as it forms the most basic electromagnetic actuator from which most other drives are inherited.

DC motors are nowadays still applied in variable-speed drives, with a power electronic supply. Advantageous is the simple construction and structure of the static converter, the high control-dynamic and its high power-density. Disadvantageous is the required maintenance of the brushes and the collector, which also limit its maximum speed to a few krpm.

The fundamental operational behaviour of a DC machine can be understood very quickly by applying the induction law on a conductor moving in a static magnetic field:

$$U_i = Nd\Phi / dt \tag{2.1}$$

The induced voltage U_i is proportional to the time-varying flux enclosed by the circuit. In the case illustrated in Fig. 2.1, the flux variation is obtained by the variation of the coil-surface A penetrated by the flux. N is the number of windings.

$$U_i = NB_\delta dA / dt = NB_\delta Ids / dt = NB_\delta l_{fe} v \tag{2.2}$$

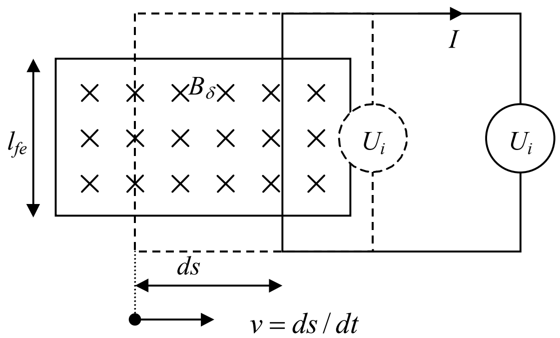


Figure 2.1: Moving Coil in a Magnetic Field B_δ.

Due to the flux variation a voltage is induced in the coil that is proportional to:

- flux density B
- velocity of the conductor(s) v

This principle can directly be used to develop a 2-pole rotating DC machine. Motor as well as generator operation can be derived from Fig. 2.2. The collector or commutator guarantees the unidirectionality of the current.

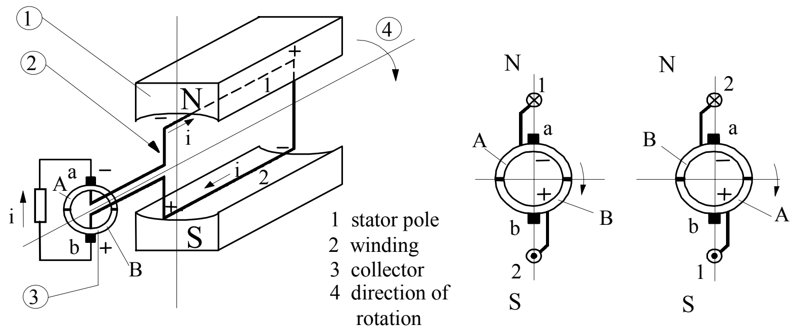


Figure 2.2: Principle of a Rotating DC Machine.

If it is assumed that the coil-surface area A covers an entire pole pitch τ it can be written:

$$A = \alpha \tau l_{fe} \tag{2.3}$$

With the rotor radius R and 2p poles in the machine, the pole pitch τ is:

$$\tau = \frac{2\pi R}{2p}, \tag{2.4}$$

the pole-flux can be calculated by:

$$\Phi = AB_\delta = \alpha \tau l_{fe} B_\delta \tag{2.5}$$

The multiplication of in the magnetic air gap field B_δ moving conductors z per winding branch yields using eq. (2.2) the induced voltage in the armature winding:

$$U_i = \alpha \frac{z}{2a} B_\delta l_{fe} v = \alpha \frac{z}{2a} B_\delta l_{fe} 2\pi R n \tag{2.6}$$

n is the speed of the rotor, $2a$ the number of parallel branches. All quantities are given in the basic unit system. With eq. (2.5) the induced voltage is finally calculated by the following expression, clearly showing the proportionality of the induced voltage or ‘electromagnetic force’ (emf) to the flux and speed:

$$U_i = \frac{z}{a} p \Phi n = k_1 \Phi n \tag{2.7}$$

Fig. 2.3 illustrates the term of the number of parallel winding-branches. The winding current is always $I = \frac{I_a}{2a}$.

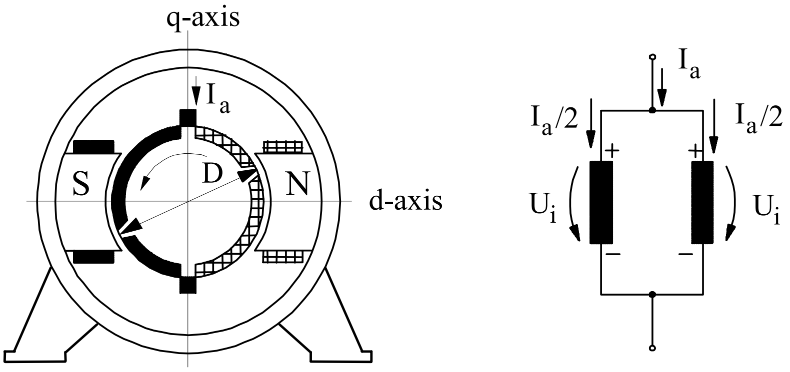


Figure 2.3: DC Machine with 2p=2 Poles and 2a=2 Parallel Winding Branches.

Supplying the DC machine with a voltage U_a at the terminals of the rotor, also called the *armature* i.e. at the brushes (Fig. 2.4), assuming a constant voltage U_f for the excitation winding and neglecting the brush-voltage drop, the Kirchoff voltage law yields:

$$U_a = I_a R_a + U_i \tag{2.8}$$

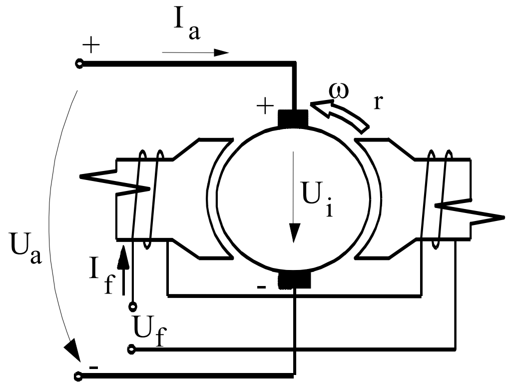


Figure 2.4: Voltage Systems for the DC Machine.

By multiplying with the armature current transforms the voltage equation (2.8) into a power balance.

$$\begin{aligned} I_a U_a &= I_a R_a + I_a U_i \\ P_{el} &= P_{loss} + P_{mech} \end{aligned} \tag{2.9}$$

It must be noted that eq. (2.9) only considers the Joule losses in the armature winding and neglects iron losses[2], friction and the Joule losses in the excitation winding. The excitation winding's Joule losses have to be considered determining the efficiency of the machine.

With the arrow system indicating the relation between voltages and currents in Fig. 2.5, the different terms for the power can be either in motor or generator operation dependent of the sign of the armature current Ia. For positive currents Ia the machine operates as a motor, respectively as a generator, if the armature current is negative.

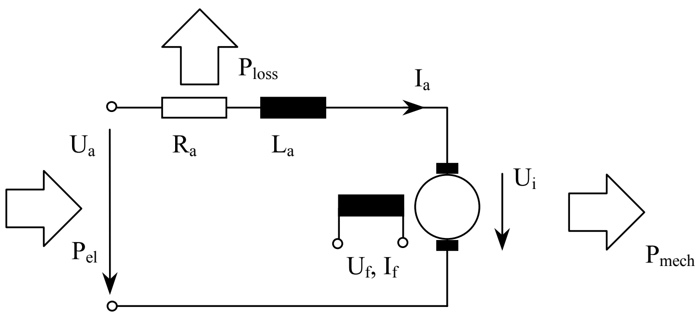


Figure 2.5: Equivalent Circuit for a DC Machine.

The relation between the power and speed of a rotating system $P_{mech} = T\omega = T2\pi n$ delivers the torque of the DC machine (2.11).

$$\begin{aligned} P_{mech} &= U_i I_a = T2\pi n \\ &= k_1 \Phi I_a n \end{aligned} \tag{2.10}$$

[2] 'Iron losses' are losses in ferromagnetic material due to changing magnetic flux. They consist of hysteresis losses (arising when the materials BH hystereris loop is circulated) and internal eddy current (induced currents) losses.

$$T = \frac{k_1}{2\pi}\Phi I_a = k_2 \Phi I_a \tag{2.11}$$

Note that the expression for the torque can also be derived by starting from the Lorentz force expression. Arranging eq. (2.8) and (2.11) yields the important equation for the relation between speed and torque:

$$n = \frac{U_a}{k_1\Phi} - T\frac{R_a}{k_1 k_2 \Phi^2} = n_0 - T\frac{R_a}{k_1 k_2 \Phi^2}\,. \tag{2.12}$$

The no-load speed of the DC machine is n_0. This expression illustrates that the speed of the machine decreases when loaded, an effect that has to be corrected through a feedback control loop. Using eq. (2.12) enables the prediction of the behaviour of the DC machine operated under various conditions and different winding arrangements.

Fig. 2.6 shows the cross-section of a DC motor to illustrate the flux path in this machine. It is obvious that due to the commutation of the rotor current, iron losses occur in the rotor and a DC magnetic flux is situated in the stator part of the machine.

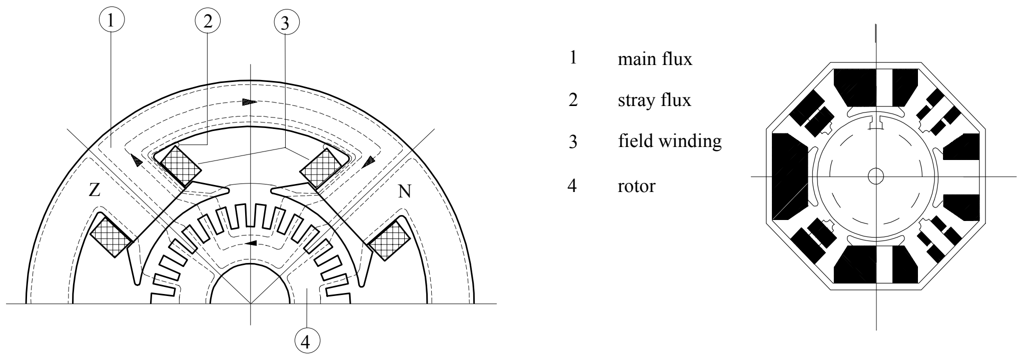


Figure 2.6: Basic Construction of a 4-Pole DC Machine With and Without Interpolar-Gap Winding.

Using the equation (2.9), (2.11) and (2.12) the behaviour and the various possible operations of a DC machine can be studied. The possibilities to control the speed of this type of machine can be derived from such equations as well.

Independently excited machine: Applying a separate voltage source to the *field winding* or using *permanent magnet* material for the stator excitation yields the basic characteristic of the DC machine (Fig. 2.7). It can be seen that this operation with constant flux can be determined by evaluating eqs. (2.11) and (2.12). The continuously change to generator operation is possible at this operation.

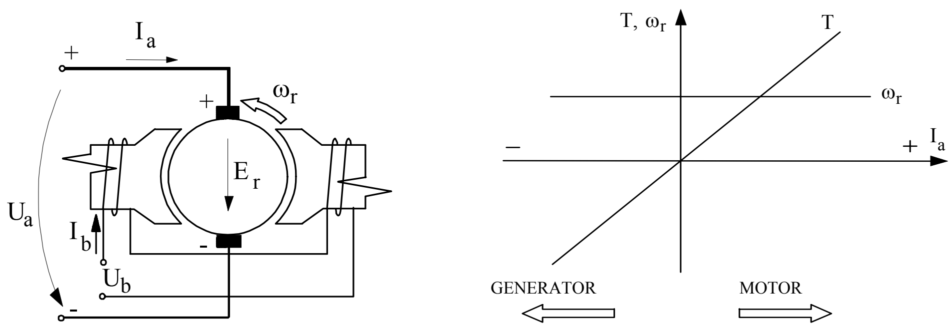


Figure 2.7: Separately Excited DC Machine and its Operational Characteristic.

Shunt or parallel excitation: Under this operation, the excitation winding is arranged in parallel to the armature winding (Fig. 2.8).

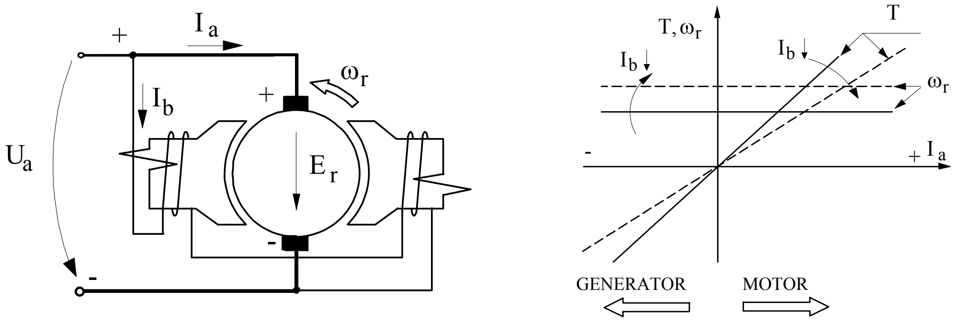


Figure 2.8: Shunt or Parallel Excitation.

Series excitation: DC Traction drives require a large torque at low speed and a low torque at high speeds. This desired characteristic can be obtained by arranging the excitation winding in series with the armature winding (Fig. 2.9). A continuous transition to the generator operation is not possible in this mode of operation. Such a machine can also be supplied by AC current, as it can be shown that the torque is proportional to the square of the current. Therefore, it is better known as the *universal motor*, which a small cheap single-phase machine. This AC type of motor can be found in the power range up to 2 kW operating household applications, such as vacuum cleaner, drilling machines etc. They are usually constructed as 2-pole motors. Its high power density is reached by operating at high speeds of about 10.000 to 15.000 rpm.

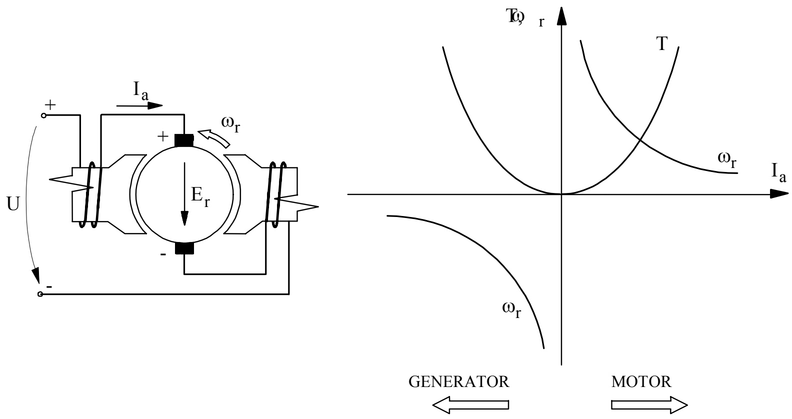


Figure 2.9: Series Excitation of a DC Motor.

3.0 INDUCTION MACHINE

The induction machine, also know as asynchronous machine, is the most widely used electrical motor in industry. The reason for this can be found in its very cost effective and robust construction. Induction machines are mainly employed as motors up to 10 MW. Typical areas of application are pump drives, vans, compressors, paper mills, etc. Sometimes induction machines are used as generators up to a few MW, for instance in certain types of wind turbines.

Induction motors are operated by a symmetric three-phase AC current/voltage system. Usually the induction motor consists of a three-phase stator winding, though smaller (cheaper) types can be constructed with single-phase AC windings. In the following section symmetrical three-phase machines for industrial applications are assumed.

Induction machines have a uniform air gap and are operated by a synchronously rotating magnetic air gap field excited by the stator winding. The rotor is rotating *asynchronously* (due to induction effects: see next paragraphs) with a '*slip*' or relative speed difference:

$$s = \frac{n_1 - n}{n} \tag{3.1}$$

With the slip definition, the various operation conditions of an induction machine are given by:

n < 0	s > 0	rotation against the rotational field (braking)
n = 0	s = 1	locked rotor (standstill)
0 < n < n1	1 > s > 0	operation below synchronism (motor)
n = n1	s = 0	Synchronism (ideal no-load)
n > n1	s < 0	operation above synchronism (generator)

Basically two rotor variants of the induction motor (Fig. 3.1) can be distinguished:

- *Squirrel cage* (Fig. 3.2): cast aluminium (or sometimes copper) bars, short-circuited by ring-shaped conductors at the end.
- Three-phase slip-ring rotor winding, the wound rotor type (Fig. 3.3): a three-phase winding is present on the rotor as well. The windings are connected to slip-rings. This type was used in the past to change speeds by connecting extra resistance externally, but nowadays it is mainly applied in large *'doubly-fed' machine*, where a relatively small power electronic supply is connected to the rotor in order to achieve a variable speed. A typical example are large variable-speed wind turbine generator, connected to fixed-frequency power grid.

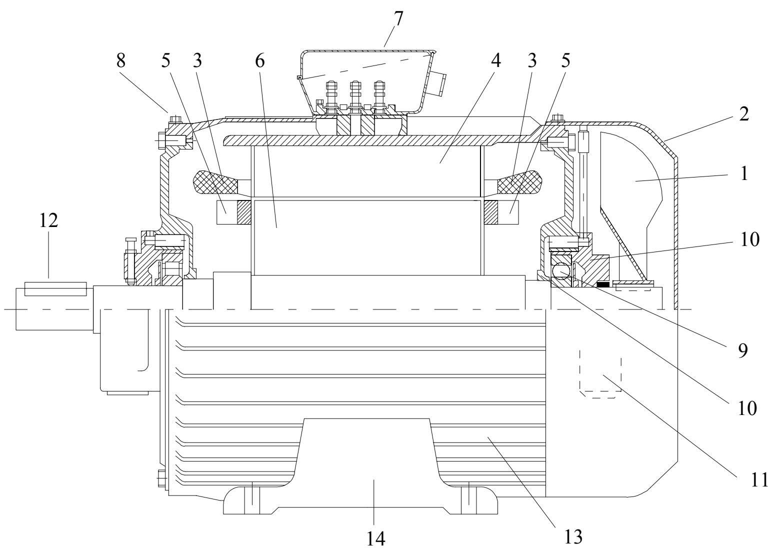


Figure 3.1: Construction of an Induction Motor. (1 ventilator, 2 ventilator cap, 3 three-phase stator winding, 4 stator lamination, 5 rotor cage (rotor bars and end-ring), 6 rotor lamination, 7 terminals, 8 grounding, 9 suspension, 10 suspension cap, 11 container for suspension oil, 12 shaft, 13 cool fins, 14 housing).

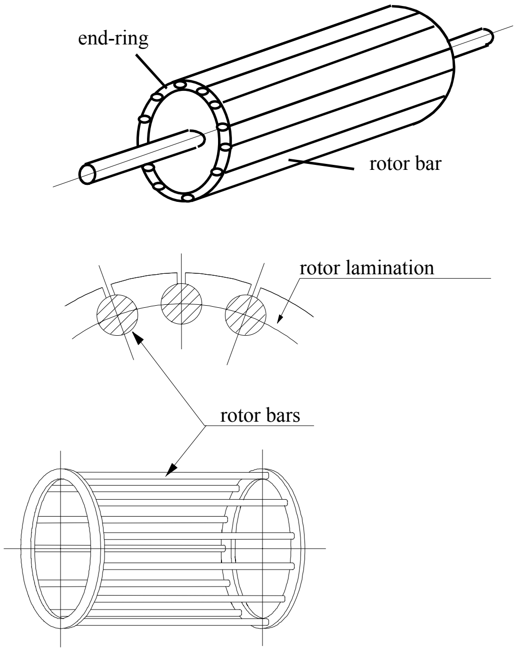


Figure 3.2: Rotor Winding Variants: Squirrel Cage.

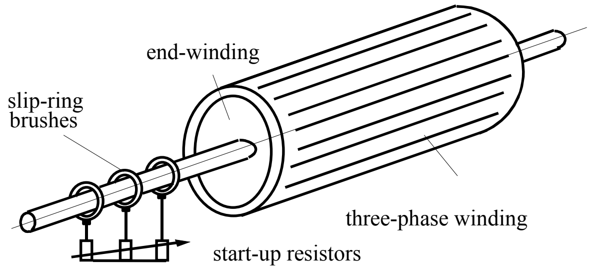


Figure 3.3: Rotor Winding Variants: Wound Rotor.

The stator is operated with the supply frequency f_1 and the rotor winding contains current and voltages with slip-frequent AC currents with frequency: $s.f_1$. Therefore, the rotor and stator are constructed with iron lamination, to prevent excessive eddy current losses in the massive conducting structures.

The stator coils are arranged in the slots of the stator (Fig. 3.4). Low-voltage windings have coils in half closed slots and high-voltage machines are constructed having pre-manufactured windings (Fig. 3.4). Concentric coils and coils with the same width can be constructed.

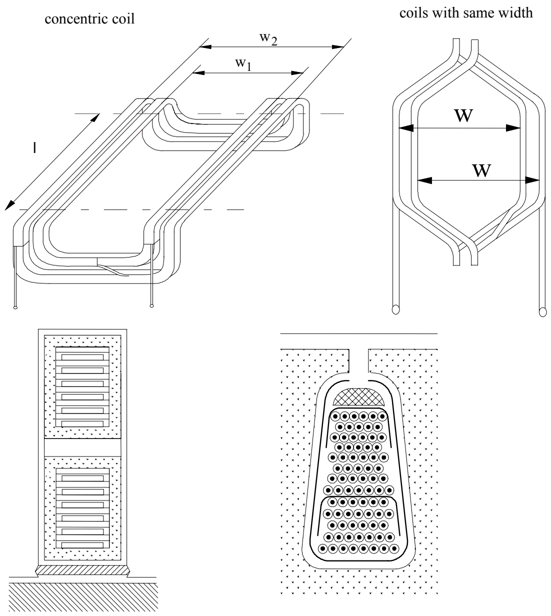


Figure 3.4: Winding Arrangements and Slot Constructions for Low- and High-Voltage Machines.

The three-phase stator winding is supplied by a symmetric three-phase AC voltage or current system. The magnitude of the winding currents must be identical in all identical winding phases and is shifted in time by 120 (electrical) degrees. The winding phases are displaced from each other by 120 (electrical) degrees in space around the inner circumference of the machine (Fig. 3.4). Under this assumption a rotating magnetic field is generated in the air gap of the machine.

This rotating magnetic field is 'sensed' by the rotor windings, seeing a changing magnetic field and hence a voltage is induced. In the closed windings a current will flow due to Ohm's law and this current's interaction with the rotating magnetic field causes the torque. If the rotor would spin at the same speed as the rotating magnetic field, no induction would take place and no torque can be developed, so this condition is only found in ideal no-load situations. When loaded, a relative speed difference is required to maintain the induction effect, so asynchronism or rotor slipping arises. This induction effect can take place up to a certain maximum, so the speed-torque range is not infinite. In case of generator operation, 'oversynchronism' occurs.

In Fig. 3.5 a squirrel cage rotor winding is represented by a concentrated equivalent three-phase winding. In the figure, index 1 denotes the stator quantities and index 2 all quantities related to the rotor. w is the number of turns of the winding phase, m the number of phases and ζ is the resulting winding factor for the fundamental frequency f_1, representing the flux weakening due to the distributed coils of the winding. Here, the three winding phases are named U, V and W. The frequency equation for the rotating machine can be written by:

$$\begin{aligned} \omega_1 &= \omega_2 + p\omega_{mech} \\ f_1 &= f_2 + f \end{aligned} \qquad (3.2)$$

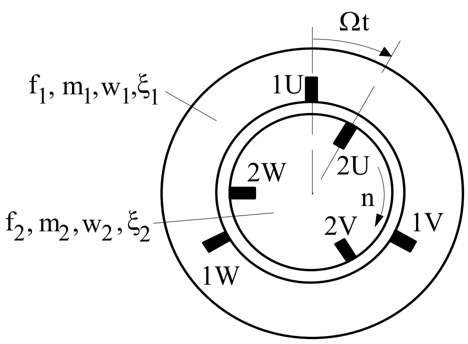


Figure 3.5: Rotor and Stator System of an Induction Machine.

Using the definition of the slip eq. (3.1) rearranges (3.2) to:

$$s = \frac{n_1 - n}{n_1} = \frac{f_1 - f}{f_1} = \frac{f_2}{f_1} \qquad (3.3)$$

and yields the determination of the slip-frequency for the rotor electric circuit:

$$f_2 = s \cdot f_1 \qquad (3.4)$$

To understand the function and to determine the operational behaviour of the machine, the induction machine can be understood as a magnetically coupled system of two winding systems with different frequency. The slip as a factor can be used to create an equivalent one-phase model (Fig. 3.6).

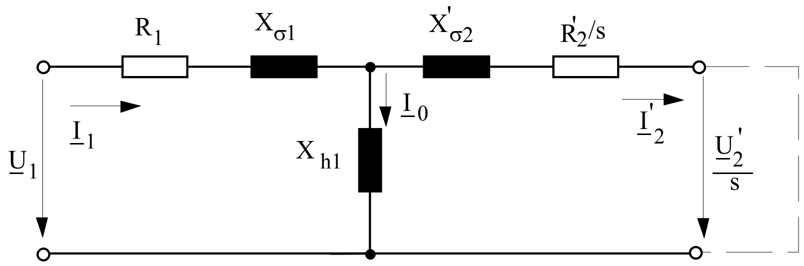


Figure 3.6: Single-Phase Equivalent Circuit Model for the Induction Machine.

The model parameters are:

- R_1: stator resistance (can often be neglected);
- $X_{\sigma 1}$: stator leakage inductance, representing the part of the magnetic field which is not mutually coupled between rotor and stator (for instance associated with end-winding flux);
- X_{h1}: main inductance associated to the mutually coupled flux;
- $X\sigma_2$': rotor leakage inductance;
- R_2'/s: rotor resistance, representing rotor losses and the electromechanical energy on the shaft; and
- U_2'/s: induced voltage in the rotor; in case of squirrel cage this is short-circuit.

With these assumptions the voltage equation for rotor and stator can be given:

$$\begin{aligned} \underline{U}_1 &= R_1 \underline{I}_1 + jX_{\sigma 1} \underline{I}_1 + jX_{h1} \underline{I}_0 \\ \frac{\underline{U}_2'}{s} &= -\frac{R_2'}{s} \underline{I}_2' - jX_{\sigma 2}' \underline{I}_2' + jX_{h1} \underline{I}_0 = 0 \end{aligned} \tag{3.5}$$

Applying an energy balance (Fig. 3.7) delivers the losses and powers of the induction machine. The internal electromagnetic torque can be determined.

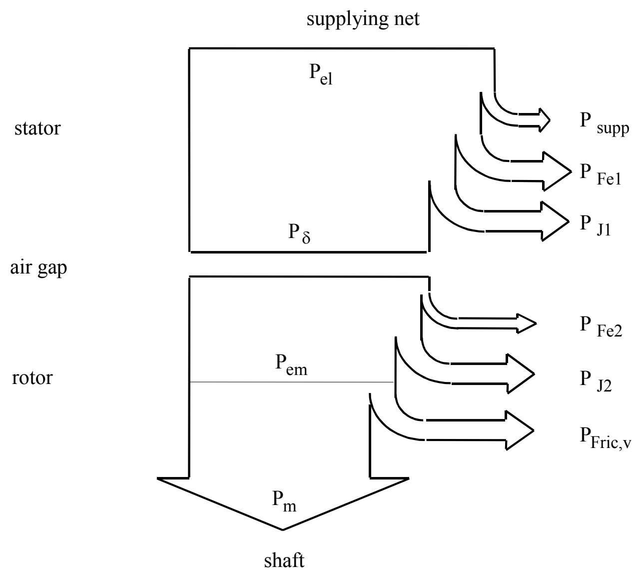


Figure 3.7: Energy Balance of an Induction Machine (Sankey diagram).

The balance delivers the air gap power

$$P_\delta = P_{J2} + P_{em} \tag{3.6}$$

with $P_{em} = (1-s)P_\delta$ and $P_{J2} = sP_\delta$ this yields the important rule of the splitting air gap power:

$$\eta = \frac{P_m}{P_{el}} < \frac{P_{em}}{P_\delta} = \frac{(1-s)P_\delta}{P_\delta} \tag{3.7}$$

Note that it is inevitable to have rotor Joule losses as this is linked to the necessary induction of the rotor magnetic field. With this rule it is obvious that an induction machine can only be operated efficiently at low values of the slip. The stationary speed-torque characteristic of an induction machine operated at the grid can be determined (Fig. 3.8).

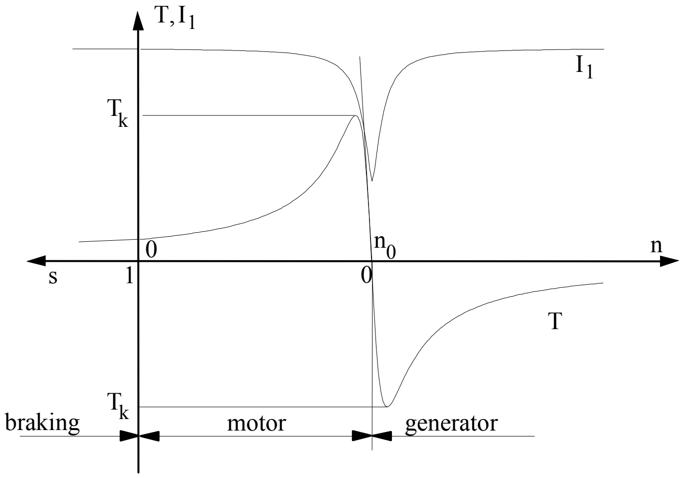


Figure 3.8: Characteristic of Induction Machines Operated at the Constant Grid.

One can prove that the starting behaviour of the machine depends on the rotor resistance at the supply frequency. Various concepts and shapes of bars are used nowadays (Fig. 3.9).

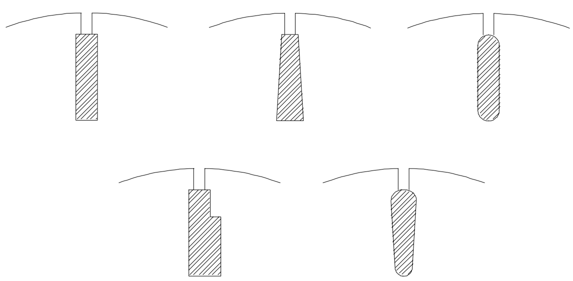


Figure 3.9: Shapes of Squirrel Cage Rotor Bars.

Typical characteristics in the operational area of induction motors are collected in Fig. 3.10. Since all the magnetic field energy needs to be supplied from outside the machine, it consumes reactive power (low cosφ).

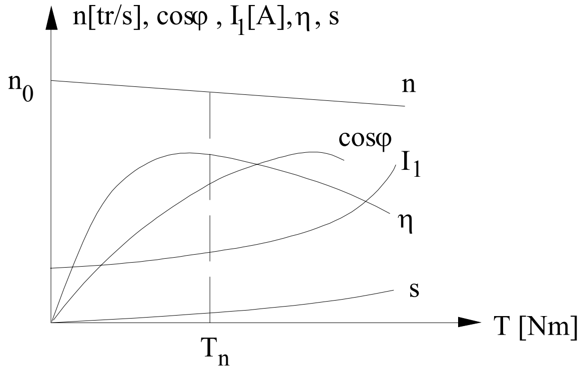


Figure 3.10: Typical Induction Motor Characteristics.

4.0 SYNCHRONOUS MACHINES

4.1 Field-Wound Synchronous Machines

Synchronous machines with a field winding are the largest electrical machines and mainly used as generators for electrical power in hydro, nuclear power or thermal power stations to transform mechanical energy to electrical energy. Synchronous machines in steady-state are rotating at constant speed, directly proportional to the supply frequency (50/60 Hz). They are constructed with a high voltage/current AC three-phase winding in the stator, also referred to as the armature, and a DC excitation winding, supplied externally, in the rotor. Thus, the rotating air gap field and the aligned rotor field are rotating at the synchronous speed (eq. (3.2); s=0). With f_2=0 the frequency equation is rewritten:

$$\begin{aligned} \omega_1 &= \omega_2 + p\omega_{mech} \\ f_1 &= 0 + f \end{aligned} \quad (4.1)$$

Due to its variable DC excitation, building up a magnetic field inside, the synchronous generator is capable to draw either lagging or leading reactive power. This is a very important feature for its operation in electricity networks.

The stator of a synchronous generator carries a winding, similar to the one used for induction machines, directly connected to the grid. The rotor has the field winding fed from an external DC source via slip rings or a rotating rectifier fed by three-phase excitation generators mounted to the shaft of the synchronous generator.

The largest sizes of generators up to 1.8 GVA are found for 4-pole turbo machines and 1.2 GVA for the 2-pole variant. Slow speed generators for hydro power stations with 2p = 40…100 have serve a power range of up to 800 MVA. A special class of machines of a few MVA for (gearless) wind turbines exists as well.

There are two different rotor constructions to distinguish:

- High speed machines with a cylindrical rotor, in slots distributed field winding and uniform air gap (turbo machines); and
- Low speed generators with a salient pole construction, concentrated field winding.

The rotor shape can be either cylindrical or with salient poles (Fig. 4.1). This has consequences for the shape of the induced voltage and the control parameter, as the inductance in the direction of the field may differ from the inductance in the quadrature direction. Cylindrical rotors are fabricated in one piece and are mainly found in machines for high speeds (<3 krpm). Large, slow machines, are often of the salient pole type as they are constructed pole by pole (e.g. huge hydro generators).

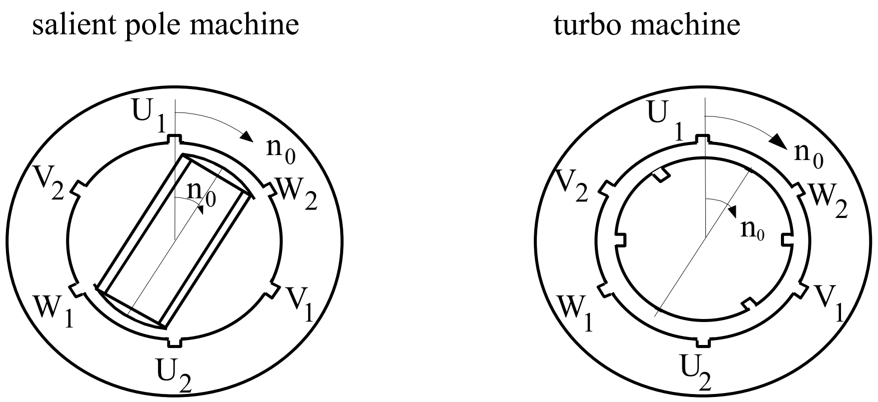


Figure 4.1: Rotor Variants of Synchronous Generators.

Due to the large dimensions of the coils of the synchronous generator, eddy currents can occur as the skin depth at fundamental frequency is smaller than the size. Here special winding arrangements, constructed as twisted bars, the Röbel bars, are required (Fig. 4.2). To transmit the copper losses out of the machine direct coil cooling is applied (Fig. 4.2).

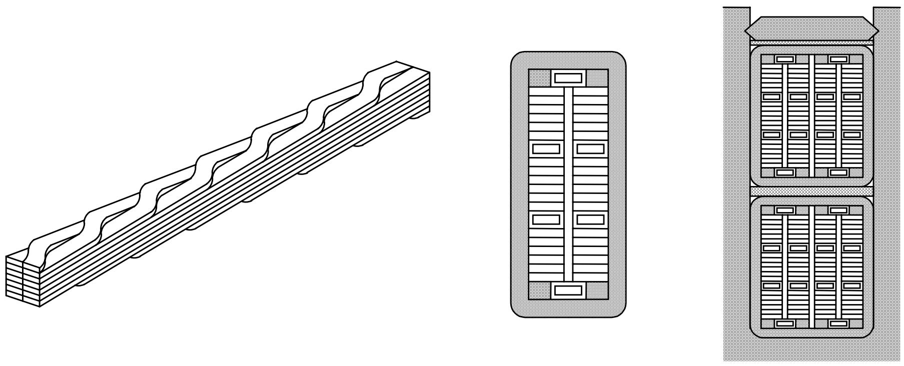


Figure 4.2: Winding Arrangement (Röbel Bars) for Synchronous Generators.

If a DC current If is applied to the field winding of the synchronous generator, a sinusoidal distributed flux is established in the air gap. The rotation of the shaft, e.g. by steam turbines, results in a revolving field in the air gap. Due to the three-phase winding arrangement a symmetrical voltage system is created. The generated voltage is proportional to the machine's speed and the exciting flux that depends on the excitation current I_f. The frequency of the voltage is obviously proportional to the mechanical speed as well.

$$f = p \cdot n \tag{4.2}$$

To avoid transients and high switching currents, several conditions must be fulfilled before the synchronous generator can be switched to the grid. In particular, these are:

- phase sequence
- voltage

- frequency
- phase

If such conditions are not fulfilled, high transients can occur and damage the machine. First the phase sequence must be controlled and eventually corrected. The synchronous generator must then be started. This is usually supported by a start-up motor. Very close to the synchronous speed, the excitation current is adjusted yielding the desired magnitude for the voltage. The frequency must now be adjusted by very slowly changing the speed of the drive, and when the phase between machine and grid are in parallelism, the machine can be connected to the grid.

To understand the fundamental behaviour of the synchronous generator the stator voltage equation:

$$\underline{U}_1 + R_1\underline{I}_1 + j(X_{1\sigma} + X_{1h})\underline{I}_1 = \underline{E} \tag{4.3}$$

for the turbo generator is used. E is the excitation voltage (emf) and U_i is the voltage generated by the resulting air gap field (Fig. 4.3). The rotor voltage equation, in DC, can be given by:

$$U_b = R_b I_b \tag{4.4}$$

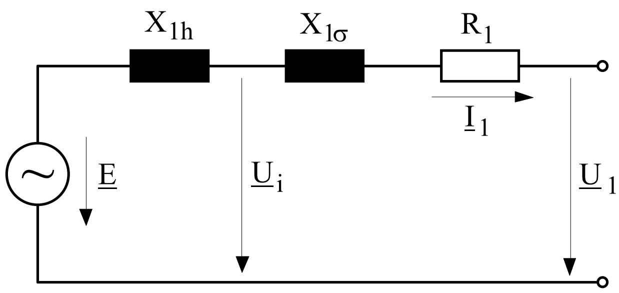


Figure 4.3: One-Phase Equivalent Circuit for the Synchronous Machine with Uniform Air Gap.

With this one-phase model it is now possible to draw the phasor-diagram of the machine.

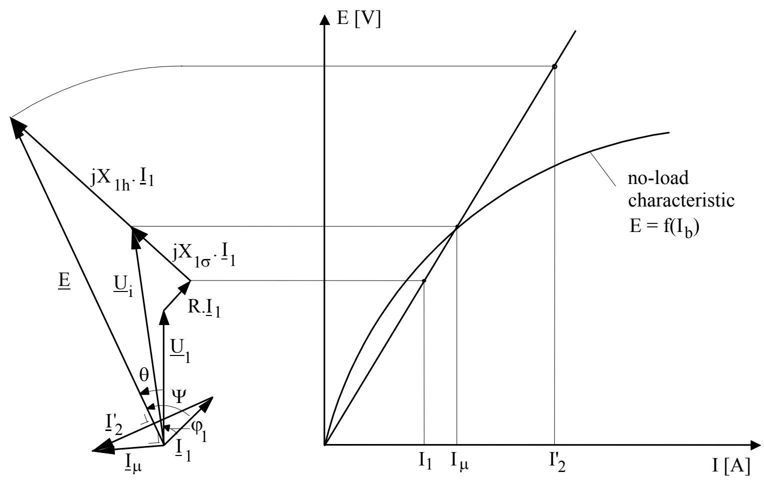
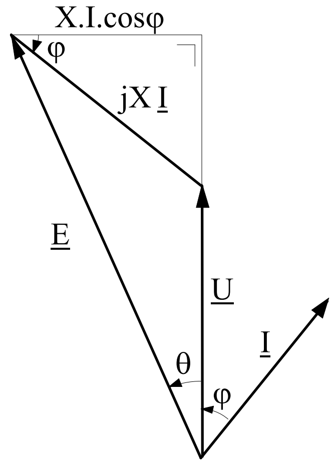


Figure 4.4: Phasor-Diagram of a Turbo Generator in Operation for Leading Reactive Power.

For simplifications and to more easily derive the operational characteristics of a synchronous generator in the following discussion, the stator resistance is neglected. The cylindrical machine and the salient pole machine are treated separately.

By using the phasor-diagram of the turbo generator with a *cylindrical rotor* the voltage relation can be determined by trigonometrically manipulations.



$$X.I.\cos\varphi = E.\sin\theta$$

$$I.\cos\varphi = \frac{E}{X}.\sin\theta$$

Figure 4.5: Simplified Phasor Diagram for the Turbo Generator.

The synchronous torque can directly be derived from the energy equation:

$$P_{mech} = \omega_1 T = P_{elec} = \sqrt{3}U_{line} I\cos\varphi \tag{4.5}$$

This yields

$$T = \frac{mUI\cos\varphi}{\omega_1} \tag{4.6}$$

a relation for the torque, depending on the terminal quantities and the phase angle of the machine. Rearranged and using the excitation voltage it can be written:

$$T = \frac{mUE}{\omega_1 X}\sin\theta = T_{\max}\sin\theta \tag{4.7}$$

With θ the load angle, to be interpreted as the angle between the magnetic field link to the rotor winding and the magnetic field linked to the stator. This expression indicates that there is a maximum load angle, 90°, so a maximum torque of the machine. It can be shown that if θ<90°, the machine is stable (Fig. 4.6).

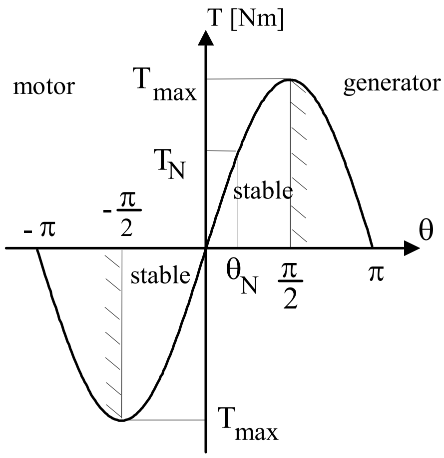


Figure 4.6: Torque versus Power-Angle of the Turbo Generator.

For the *salient pole generator* variant the magnetically anisotropic rotor geometry is used to derive the torque characteristic. The equations are transformed into a d/q-axis system (Fig. 4.7) to determine the influence of the non-uniform air gap on the machine behaviour. The index d stands for the direct axis and q for the quadrature axis of this co-ordinate system.

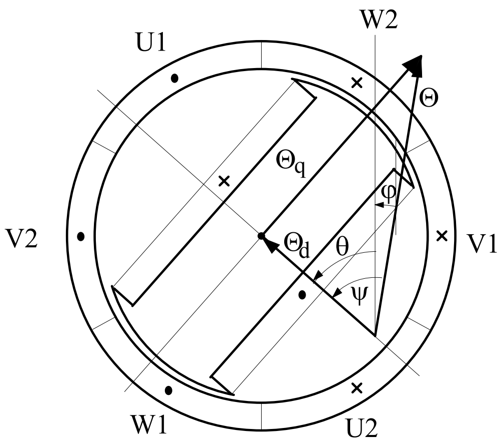


Figure 4.7: d/q Axis System for the Rotor of the Salient Pole Generator.

The flux density distribution illustrates the influence of the non-uniform air gap (Fig. 4.8).

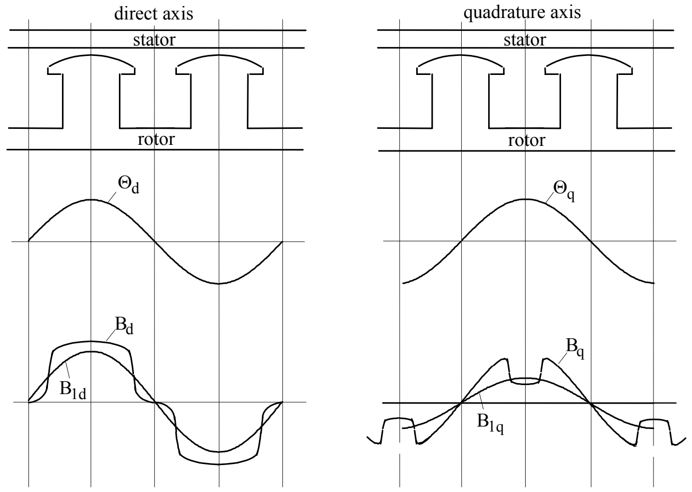


Figure 4.8: Air Gap Field Distribution in d and q Axis of the Generator with Salient Poles.

The fundamental of the flux density distribution, yielding the induced voltage (Fig. 4.7), can be calculated by using the d/q field factors:

$$B_{1d} = C_d B_1$$
$$B_{1q} = C_q B_1 \tag{4.8}$$

The factors can be found in the range of $C_d = 0.8, \ldots, 0.9$ and $C_q = 0.4, \ldots, 0.5$. The transformation for the reactances/inductances (Fig. 4.9) into the d/q co-ordinate system can be performed by using

$$X_d = X_\sigma + C_d X_h$$
$$X_q = X_\sigma + C_q X_h \tag{4.9}$$

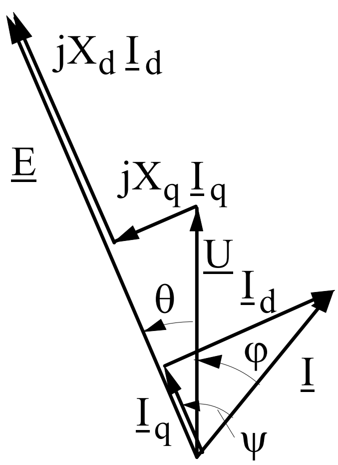


Figure 4.9: Phasor-Diagram.

The voltage equation

$$\underline{E} = \underline{U} + jX_q \underline{I}_q + jX_d \underline{I}_d \tag{4.10}$$

with the currents

$$\underline{I}_d = I \sin \Psi$$
$$\underline{I}_q = I \cos \Psi \qquad (4.11)$$

yields the desired torque characteristic for the salient pole synchronous machine:

$$T = \frac{m}{\omega_1} \cdot \left[\frac{U.E}{X_d} . \sin \theta + \frac{U^2}{2} . \left(\frac{1}{X_q} - \frac{1}{X_d} \right) . \sin 2\theta \right] \qquad (4.12)$$

It can be noticed that the torque consists of two components, a synchronous torque T_1 and a component caused by the asymmetry of the rotor, a reluctance torque T_2 double the power-angle dependent (Fig. 4.10). Due to the reluctance torque the stability range of this generator is decreased in this case.

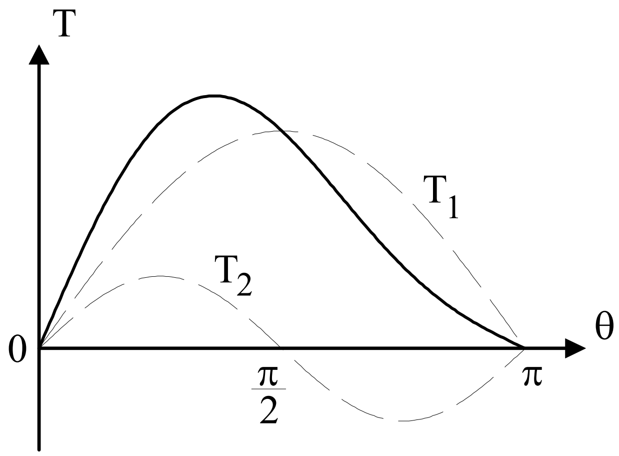


Figure 4.10: Torque Characteristic of a Salient Pole Synchronous Generator.

Dependent on the active and reactive current

$$\underline{I} = Ie^{-j\varphi} = I(\cos \varphi - j \sin \varphi)$$
$$= \frac{E}{X} \sin \theta + \text{ (active current)} \qquad (4.13)$$
$$\frac{E \cos \theta - U}{X} \text{ (reactive current)}$$

of a synchronous machine its working can be distinguished in four quadrants (Fig. 4.11).

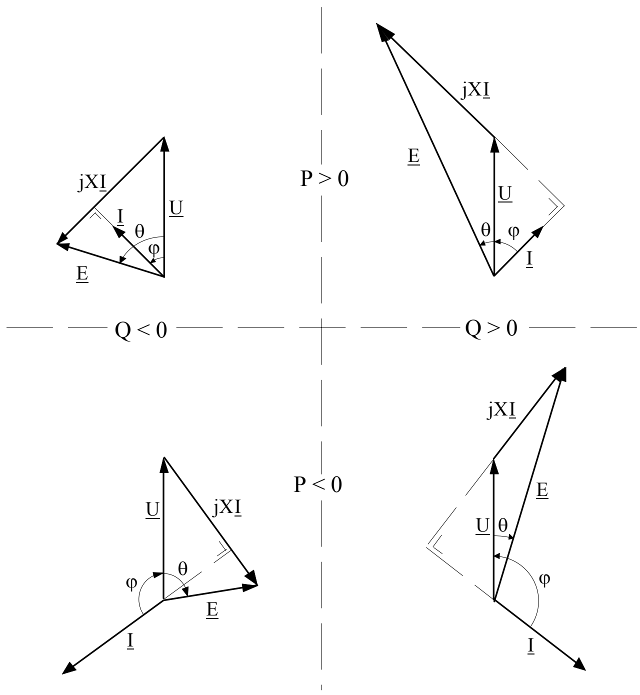


Figure 4.11: Working Range of Synchronous Generators.

Due to the possibility of introducing a DC current in the field winding and due to the fact that the machine is connected to the grid, the excitation current determines the point of operation. The machine is capable to supply the grid with capacitive or inductive currents. The 'V-curves' illustrate the possible working range for this operation. They represent the lines of constant active power. It must be noticed that the generation or consumption of reactive power is independent from the mechanical power of the machine.

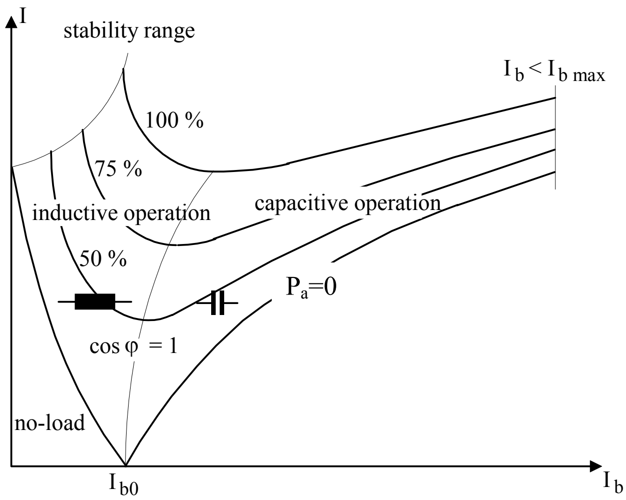


Figure 4.12: V-curves (curves of constant active power) of a Synchronous Generator.

The limitations for the working range are given by the

- maximum load angle $|\theta| \le \frac{\pi}{2}$

- maximum mechanical power $I_N \cos\varphi \leq \frac{T_N}{\frac{m}{\omega_N}.U_{N,phase}}$
- maximum excitation current $I_b < I_{b\max}$
- maximum stator current $I < I_N$

Figure 4.13 shows these limitations in a diagram for constant excitation.

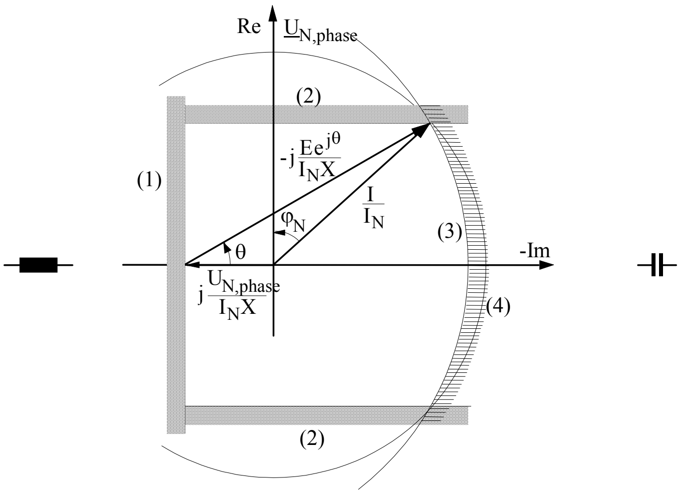


Figure 4.13: Limitations of the Working Range of Synchronous Generators.

Often the rotors of large synchronous machines are equipped with a small squirrel-cage, the damper cage, to stabilize the machine in case of large transients and/or to start up the machine.

4.2 Permanent Magnet Motors

For smaller synchronous machines, it becomes more advantageous to the use permanent magnets to generate the rotor field (Fig. 4.14). The above derived equations and behaviour stays valid, with the limitation that the variable excitation is to be replaced by a fixed term.

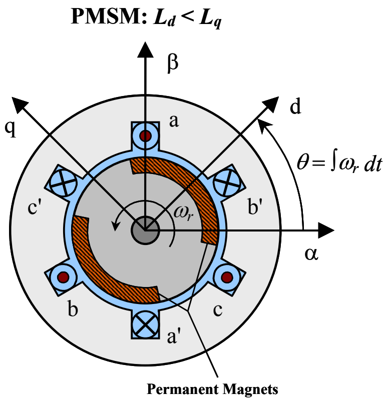


Figure 4.14: Permanent Magnet Synchronous Machine with Surface Magnets.

Several different constructional variants exist, differing in the positioning of the magnets: for instance, surface mounted or embedded. Depending on the rotor construction, which determines X_d and X_q, the reluctance torque can be positive or negative. The used magnets are usually powerful NdFeB magnets. Often an extra bandage, e.g. fibre-glass, is necessary to keep the magnets in position. Fig. 4.15 shows an example if a PMSM with surface mounted magnets.

Figure 4.15: PMSM Rotor and Stator and Encoder.

Such machines exist in a range up to 20 kW, with speeds up to 10 krpm. The main application for such machines is robotics (servo-drives), but new markets, e.g. hybrid electrical vehicles and microturbines, arise.

These machines cannot be run off the grid (no damper cage) and need to be supplied from a power electronic converter, supplying the correct frequency. Such a frequency converter may supply a sinusoidal voltage waveform or a square-wave voltage, with many harmonics. This simpler supply has disadvantages in terms of noise and losses, but comes with a simpler voltage inverter with a much lower switching frequency. Such a square-wave voltage supplied PMSM is known as a *'Brushless-DC' machine* (BLDC) or Electronically Commutated DC-machine due to its analogy is operation to a DC-machine, but considered inside-out. Because of the limited number of switchings per electrical period (six), a high fundamental frequency can be generated, making this a cheap drive for high speeds (few 10 krpm).

4.3 Switched Reluctance and Stepper Motors

Synchronous machines can be operated on reluctance forces as well. In general this yields robust simple machines as no rotor windings nor magnets are involved. Two types of such a reluctance-based synchronous machine are popular:

4.3.1 Switched Reluctance Machine

A switched-reluctance machine (SRM) contains a solid rotor with a series of poles. The stator is not built with a distributed winding in slots, but uses concentrated poles. To be able to generate torque in any position, these pole numbers must not be different. The stator pole pairs are exited one-by-one, making the rotor follow. Hence a single-phase power electronic circuit per stator pole pair is required.

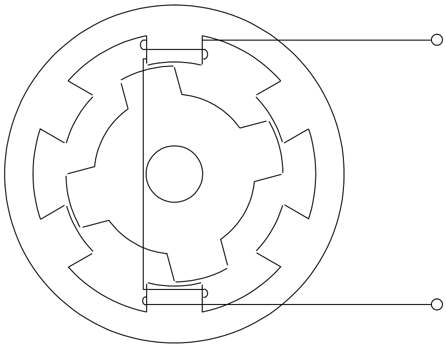


Figure 4.16: Example of an SRM, with the Connections for One Stator Pole Visible.

As these machines are very simple and robust and can be made quite efficient, they gain popularity. It is possible to use them as high-speed machine.

4.3.2 Stepper Motor

The stepper motor can be considered the 'small brother' of the SRM. It also works on reluctance torque, but in general has many more rotor poles. The purpose of this small machine (power: a few W or tens of W) is positioning in small robotics applications: by putting a current pulse on a pole, the motor jumps to the next stable positions. Sometimes a magnet is present for holding torque.

Figure 4.17: Stepper Motor Cross-Section.

5.0 ELECTRICAL DRIVES

Nowadays, an electrical machine is often not operated on its own. It is just a piece a broader system (Fig. 5.1), called a drive, together with:

- the load;
- sensors, such as encoders, transducers;
- power electronics for the motor;
- the controller(s); and
- transmission system.

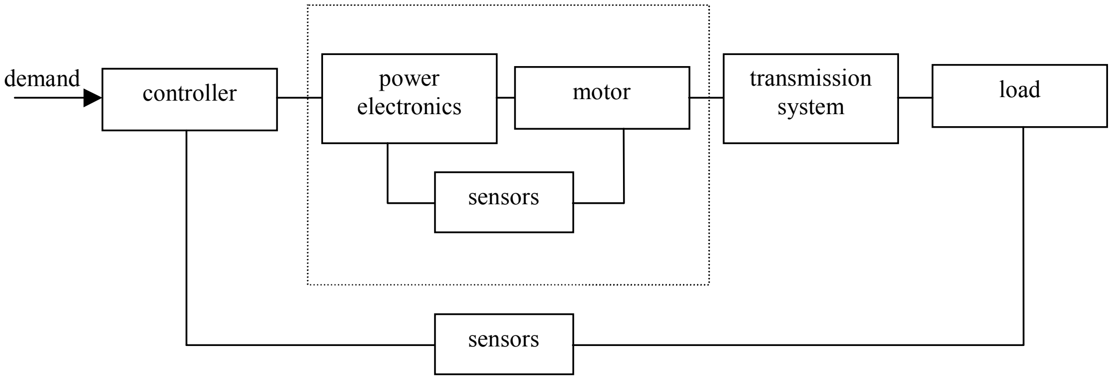


Figure 5.1: Block Diagram of a Typical Drive System.

The power electronics and motor usually are considered as integral package. In order to select the appropriate system elements, various data have to be collected. Table 5.1 shows a collection of the most important ones.

Table 5.1: System Requirements to be Considered during Selection of Elements for a Drive System

load	speed
	acceleration & deceleration
	motion profile
	dynamic requirements
	forces, torque
environmental aspects	safety
	EMC aspects
	climatic and humidity ranges
	supply specifications
	electrical compatibility
life-cycle costs	initial costs
	operational costs
	maintenance costs
	disposal costs
system integration	mechanical fitting
	bearing and couplings
	cooling
	compatibility with existing systems

One of the main design decisions that have to be taken, is the selection of an appropriate motor technology for the requirements of the particular application. For instance, Table 5.2 shows the requirements of a servo drive in robotics. With the rapid development in this field, a number of options are available. Each option will have benefits and disadvantages. In the consideration of the entire drive, the motor determines the drive's characteristic. Furthermore, the motor determines the selection of the power electronic converter and the control requirements.

Table 5.2: Requirements of a Servo Drive

high ratio speed/torque
four-quadrant operation
high torque at standstill
high overload capability
low torque ripple
quiet operation
high ratio power/weight
high system reliability

A wide range of possibilities exists. However, only a limited number of combinations will have the characteristic necessary. Possible candidates for the application in Table 5.2 could be:

- Brushed, permanent magnet, direct-control DC motor equipped with PWM controller;
- Brushless, permanent magnet, DC motors;
- Vector or flux controlled AC induction motors; and
- Stepper motors.

With the exception of the brushed DC motor, all others are totally depending on their power electronic converter. Therefore, they are to be treated as integrated drives. Fig. 5.2 shows the various possibilities for the selection of the drive elements. From this figure, it is obvious that the entire drive consists of the five elements shown in Fig. 5.1.

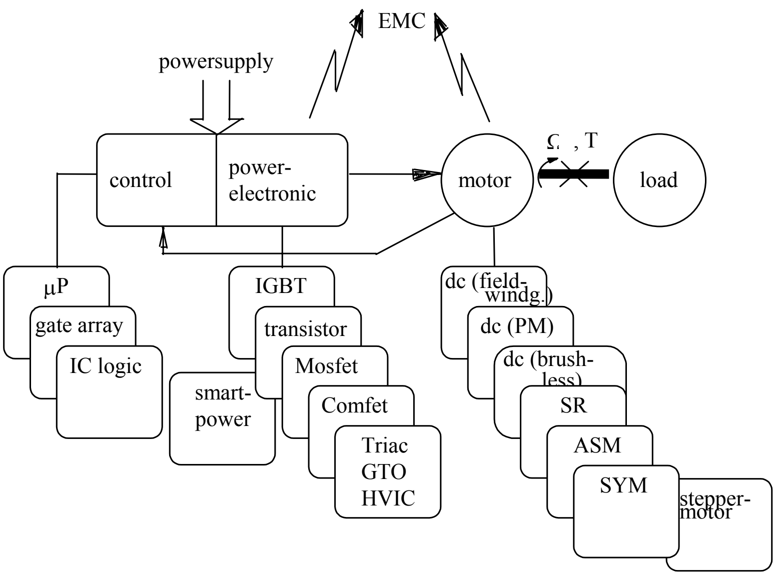
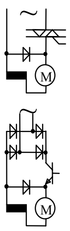
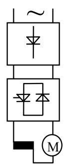
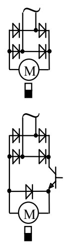
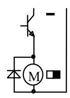
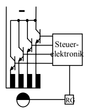
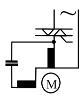
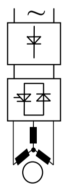
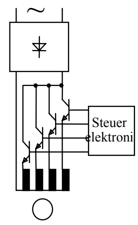


Figure 5.2: Overview of Possible Drive Systems.

As mentioned, the selection of the appropriate components of the drive system has to be done very carefully. This can be considered to require the collection of data and its detailed analysis. The design parameters of the mechanical transmission system of e.g. a machine-tool drive must be identified at the earliest possible stage. It must be realised that the entire system will be subjected to detailed design changes as development proceeds. The selection of the motor, its mechanical system, the required power electronic and control strategy is by necessity an iterative process. Any solution is a compromise. To be able to select the appropriate components of the system, a structured way of making decisions is required. Therefore, the basic principles and function of combinations of the components have to be known. Table 5.3 collects the basic combinations of electrical motors combined with the required of power electronic circuits.

Table 5.3: Schematic of Typical Power Electronic Converters for Various Motor Applications

	self-lead motors					external-lead motors			
type motor	universal-motor		PM- (fieldwinding)		EC- (PM-rotor)	asynchronous motor	synchronous motor		
			mixed voltage motor	DC-voltage motor			PM	SRM	stepper motor
speed control	gatin control 	PWM 			switching logic rotor position sensor 	gating control 	PWM 	switching logig 	

In general, once the overall application, the speed and torque requirements are identified; various combinations can be selected to form the first step of the drive development iteration. Further selections of combinations may be done comparing benefits and disadvantages and then by using the manufacturer's specifications and data sheets yielding in a second phase a detailed ranking of the combinations. Here, valuation by computer simulations is commonly used to validate the selected combinations.

Some basic selection considerations are:

- Start-up condition: The peak torque required by the load application must be less than both, the stall torque of the motor and the peak torque of the motor, which can be produced with the power electronic chosen.
- Rated operation: The root-mean-square (rms) torque required by the load application must be less than both, the rated torque of the motor and the rated torque of the motor, which can be produced with the power electronic chosen.
- To ensure operation even at voltage fluctuations in the supply: The maximum speed required by the load application must not be higher than approximately 80% of the maximum no-load speed of the motor-power electronic combination.

The operation regime has to be studied when a motor and its associated power electronic converter are selected. In general, two types of operational duty load applications can be distinguished: continuous or intermittent:

- For the continuous load duty, the time for accelerating and decelerating the drive is not critical. The maximum required torque (external load plus the drive-train's friction) has to be provided on a continuous basis. The peak torque and the average torque requirements are not significantly different when compared to the continuous torque. Motor and controller are chosen primarily considering the maximum speed and continuous torque requirements.

- In contrast to the continuous load duty acceleration and deceleration of the load forms a significant part of the motor's duty cycle at operation at intermittent duty. In this case the entire inertia of the moving system (motor + load) must be considered when the acceleration torque is being determined. Therefore, the acceleration torque, the friction torque and any additional continuous load torque present during acceleration must be exceeded by the peak torque capability of the integral drive. In addition, the drive's continuous torque capability must exceed the required average torque resulting from the worst-case positioning move.

The considerations made are illustrating that a detailed analysis of the overall mechanical drive system is required for the design. Whatever motor is chosen for the system, the dynamic relationships within the mechanical drive system are fundamental to the system selection and have to be considered in an early stage of the design.