Mechatronics for elevator installers and technicians

Continuation of articles appearing in Lift-Report 1/2001 (page 50) and 2/2001 (page43)

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1 The electromechanical basis for primary elevator drives

Before discussing the drive motors used in elevator systems, we want to explain in this section the physical basis upon which the most frequently used types of elevator motors operate.
Electrical drive equipment makes use of the laws of electrodynamics to convert electrical energy. The forces imposed upon the armature of an electric motor are described with the concepts of electrodynamics force (sometimes referred to as Lorentz force). When electrons pass through an electrical conductor located within a magnetic field, then a force is imposed upon this conductor, to move. Conversely, current will flow within a conductive loop when it is moved inside a magnetic current. Electrodynamics can be easily described by way of the Flaming`s left-hand rule

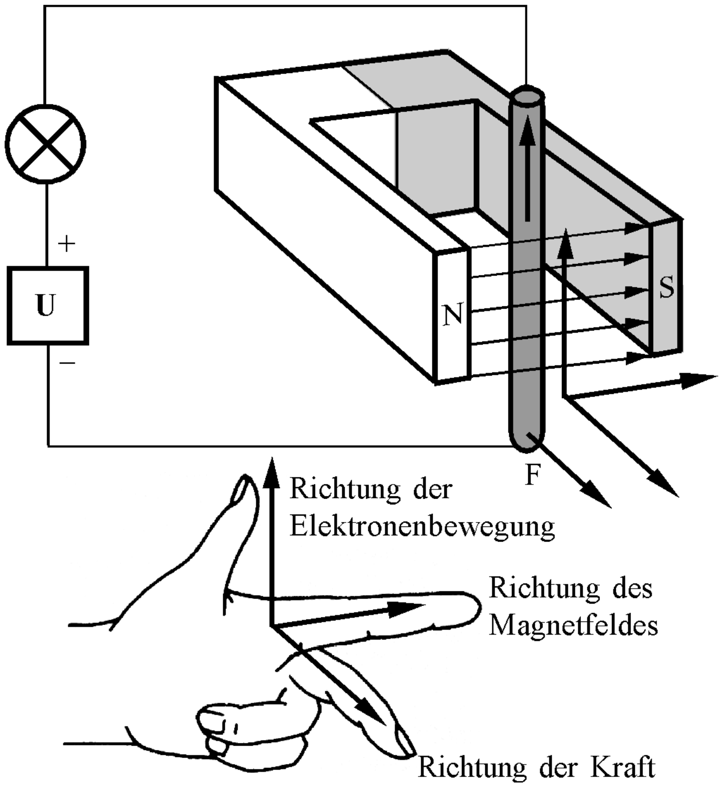
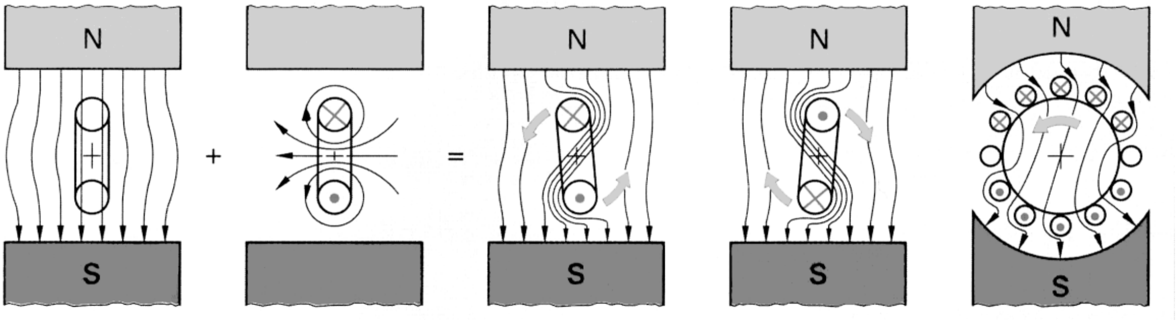


Figure 10

In simplified terms, the force „F“ acting upon a conductor which exhibits a length of „l“ and which is exposed to magnetic flux density „B“ is: F=I x l B
Conversely, if a voltage is generated within a moving conductor this will be described (in accordance with Faraday`s law-second circulate law) by the differential equation Uind = -dF/dt where „F“ designates the magnetic flux. If one were to connect the ends of this conductor, then the current will flow through the conductor and will generate a magnetic counterforce. This phenomenon is explained by the so-called Lenzian rule which in turn explains the development of torque in an electric motor. It is irrelevant whether we are dealing with a DC motor or an asynchronous or synchronous AC motor.

The degree of efficiency achieved in the conversion of electrical into mechanical power (and vice versa) will depend on the type of motor selected. The previous article explained how the degree of motor efficiency was expressed in the factors reflected in the curve for the response characteristics (see Figure 9).
A simple DC motor provides the best illustration of how the armature in the motor can be set in motion (**Figure 11**). In Figure 11a only the field of our DC motor is switched on; no force develops at the armature (here shown in simplified fashion as a loop of wire). In Figure 12a only the armatures is energised; here again, no torque can be developed. Only when both the armature and the field are energised does rotational torque occur. In Figures 11C and 11d we have achieved opposite directions of rotation by inverting armature polarity. The same effect can be achieved by reversing the polarity of the field current. Figure 11e shows the power exerted on a drum-type armature of the type employed in DC motors equipped with commutator brushes.
The DC motor with commutator brushes and external excitation is of significance today only in use as DC gearless winches for high travel speeds at high payloads. This is actually not quite justified since – aside from the Leonard dynamic converters normally used in the past to supply the required DC current – the efficiency of these DC motors with their relatively simple electrical control concept provides very good results in elevatortechnology.



11a **11b** **11c** **11d** **11e**

When upgrading older systems of this type it has in the meantime become possible to leave the DC motor in place. Here one discards the Leonard converter and the outdated thyristor technology. Modern DC converters work with transistorised power output stages and pulse with modulation; the conventional tachogenerator is replaced with a more precise and higher quality rotational angle transducer. The later increases the motor`s speed adjustment range by a factor of from 10 to 100 and makes possible stabile torque under standstill conditions (without requiring load measurement or sensing). In brush-type DC motors the stator contains the exciter coil (in smaller machines this may be a permanent magnet) and the commutatingpole winding, together with the compensation winding. The commutating pole winding suppresses brush arcing would otherwise be created at the collector by the leakage flux as contact breaks (in order to invert polarity).

The compensation winding also protects the collector by compensating for the armature reaction, magnitude of which is a factor of the load. Armature current thus flows through the commutating pole and compensation windings. The compensation winding is not always present in the motors and thus it is necessary, when dealing with such motors, to ensure that the limiting curve for commutation is observed so that the motor will not be damaged by excessive speeds at heavy loading situations. Since the load torque at constant excitation practically defines the armature current, the overload limit for the DC motor will have to be monitored by way of external armature current limiting circuitry. The DC motor delivers very uniform torque if helical grooves are provided in the rotor.

That is why this is still a favourite for use as the load source in testing equipment. Since the exciter winding can be driven separately, the DC motor can also be run down into the field attenuation range. In such a situation the speed of the motor rises beyond its ratings while performance remains the same. Where the exciter field is too weak, however, there is a hazard that the rotor can be destroyed by the rapidly rising centrifugal forces acting on the armature. That is why the tachogenerator or the rotation transducer and the field current have to be monitored. In addition to the DC motor with external excitation or a permanent magnet, there are also DC shunt-wound and the DC series-wound versions, neither of which is used in elevator applications. The Dc motor with external excitation can be explained by way of an equivalent circuit diagram which is easily understood .

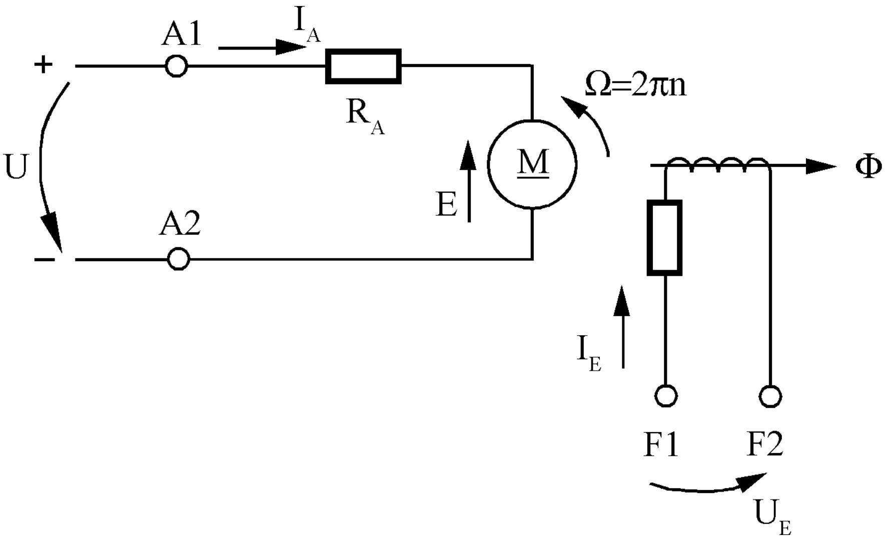


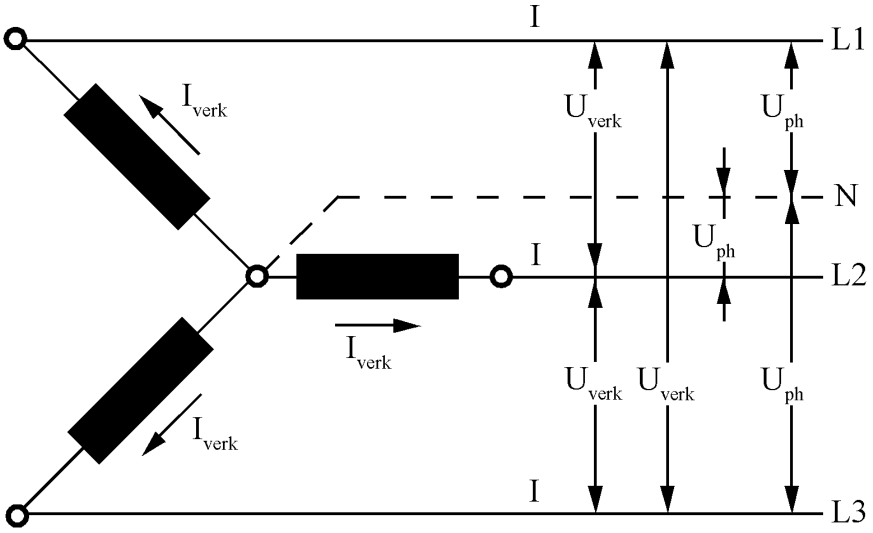
Figure 12

In the elevator industry the faster DC motors, which were connected with the lifting equipment proper by way of worm gearing, were replaced by the asynchronous at an early date. Only in gearless applications and in tall buildings will one still find DC drive principles is nonetheless very important because we want to use it to explain the important concept of current-controlled field orientation in asynchronous and synchronous motors, the state of the art at present.

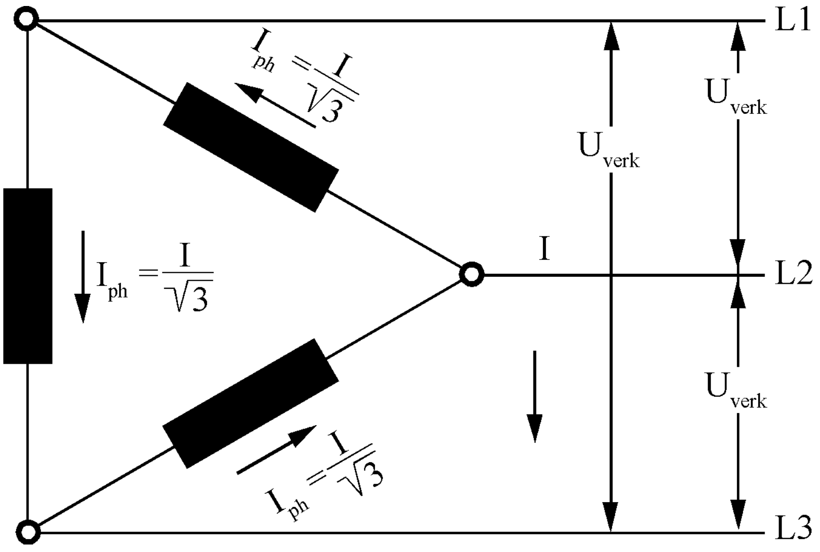
2 The asynchronous and synchronous motors in the primary lift drive

The 3-phase asynchronous motor is the type most frequently employed in elevators. In early elevator engineering the motor was, as a rule, built as a single- or two- speed unit with travel velocity being regulated by way of pole switching (using relays) or thyristor voltage dividers. In both case a special „soft" motor response curve was selected, representing a compromise between the smallest possible star-up current and ideal torque development. Today elevator moors have much „harder" response curves since they no longer need be supplied at a fixed frequency (e.g. 50 or 60 Hz). Thanks to modern frequency inverters they can always be supplied with the „U/f" which is exactly right for them and the situation.
The most important distinction as against the DC motor is that no segmented collector with brushes is required for commutating. The required rotation field is generated by phase-offset DC currents. To achieve this, the armature and the field change places (as seem from the mechanical viewpoint). In the case of the synchronous motor the rotor is equipped with a permanent magnet rotor (if external excitation is used, then the required energy will be applied by way of two slip rings). In the reluctance motor, on the other hand, the only rotating component is a star-shaped, laminated core. (This rotor requires

neither a magnetisation coil nor a cage winding nor any magnets since it is pulled along by the stator`s rotating magnetic field). In the asynchronous motor a cage made of closed conductor loops rotates within the rotor. (In the slip-ring motor these conductors exit the unit by the way of 3 slip-rings which simplify starting the unit. This motor is no longer of any significance in the elevator industry; it is mentioned only in the interest of completeness). The asynchronous motor is based fundamentally on the effect explained by the Lenzian rule.
The rotation field (in a 3-phase system) is generated by three AG voltages which are applied to the coils in the AC motor at the same frequency but phase-offset by 120°. Here we differentiate between star (or Y) and delta (or triangle) circuitry (Figures 13/14).



In the circuit (**Figure 13**) is the preferred arrangement in the AC motor used for lifts.



In the delta circuit (**Figure 14**) the full voltage is applied to the coils. The following, very important, interrelationship prevails in any motor identified by a data plate reading „400 V at 50Hz in star".
As suggested, it may be operated either at the typical 50 Hz and 400V in the star arrangement.

At the same power level, however, this motor could also be operated with the typical 50 Hz and 230 V in the delta circuit. The lower voltage demands greater phase currents by a factor of √3 (or about 1.73205). If we assume that we have available a network with about 87 Hz and that the delta circuit will handle power 1.73 times higher, then we achieve 1.73 times the performance without having to change the physical size of the motor. The 87 Hz response curve is, in practice, generated by frequency inverters. Today\`s static frequency inverters free us of the need to wind motors to match the 50 Hz line frequency. The so-called U/f curve (rated working point for voltage and frequency) can today be matched exactly to the torque and speed adjustment ranges in the application. Prior to the invention of frequency inversion technology, changes in torque and working speeds were possible only by adjusting the number of poles. In this regard we should make note of the following, important points:
A 4-pole machine running at 50 Hz has a typical no-load speed of 1500 rpm.
A 2-pole machine running at 50 Hz has a typical no-load speed of 3000 rpm.
A 4-pole machine running at 100 Hz has a typical no-load speed of 3000 rpm.
Thus both frequency and the number of poles are determinant for speed. (The literature often refers to the „number of pole pairs“ instead of „number of poles“. A 4-pole motor will have 4 poles or 2 pairs of poles. In this article we always use the term „pairs of poles“).
If we express the above interrelationships in a formula, then we can easily determine either the no-load speed (synchronous speed), the number of poles or the rated frequency of the motor if any of these parameters should be unknown (rearranging the formula).

Example: $$\frac{2 \times 50\text{Hz}}{4 \text{ poles} \times 60 \text{ s}} = 1500\text{rpm}$$

and general: $$\text{Rated no-load speed (rpm)} = \frac{\text{Rated motor frequency (Hz)}}{\text{Number of poles for AC motor} \times 120 \text{ s}}$$

A further important interrelationship explains the „U/f“ ratio for the AC motor:

A 4-pole machine which runs at 1500 rpm on 400 V, 50 Hz, would – when running on only 25 Hz-rotate at 750 rpm and require motor voltage of 200 V. If we have this machine run at 100 Hz, however, then the speed will be 3000 rpm and 800 V would be required for constant torque.
Put in simplified terms, it follows that the speed of an AC motor can be regulated by (ideally) increasing both the voltage and the frequency proportional to the speed. That is why we term this as U/f control (U/f response curve) In the case of an asynchronous machine it is possible to control only the voltage (phase gating)and in this case high losses will be encountered in the AC machine due to the slip, which is engineered for the maximum frequency value. It is this so-called slip frequency which we use to designate the difference between the motor rotation field and the actual mechanical rotation speed at the shaft. Torque can – in the case of the asynchronous motor – also be generated exclusively by slip. This is the source of the term asynchronous (in contrast to „synchronous“ in the reluctance and synchronous designs). No-load speed, which is nearly synchronous, will never be encountered in the asynchronous machine when operating as rated. Thus we will always find a slightly lower speed (e.g. 1440 rpm as compared with 1500 rpm indicates that 60 rpm of slip will appear in this motor at rated load). We should thus take note of the following interrelationship.

The difference between no-load speed and nominal speed is the slip speed. A large difference indicates that the motor exhibits more efficiency, a low cosine-phi value (and thus high reactive power) but low startingcurrent at relatively high starting torque if this is connected direct to fixed line frequency. Motors of this type have a „soft" response curve and are used in systems which are equipped only with thyristortype voltage dividers or simple pole switching under relay control. The rotors in these motors are equipped with a special type of short-circuit winding in order to generate artificial resistance (silumin rotors). These expensive and loss-prone rotors are not required when using frequency inverters. Motors designed for frequency controlled/or frequency regulation have „harder" curves with better cosine-phi values and lower slip speeds.

To understand the asynchronous motor in the equivalent circuit diagram we start simply with the equivalent diagram for a transformer since an asynchronous motor is (in principle) a 3-phase transformer whose secondary circuit is shorted. In fact, this short circuit will cause the fuses to blow if the motor is blocked or at a standstill, provided that the motor exhibits a good cosine-phi value and is not operated at „U/f". A slip-ring rotor, in which the secondary winding is accessible, could thus also be used as a transformer if one were to stop its rotor. As in the transformer, the copper loss, leakage loss and iron loss are reflected in the equivalent circuit diagram. The following speed and torque curves result:

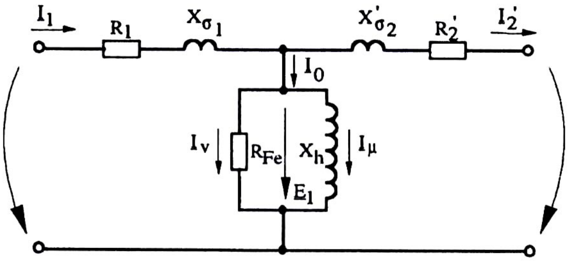


Figure 15 (Transformer)

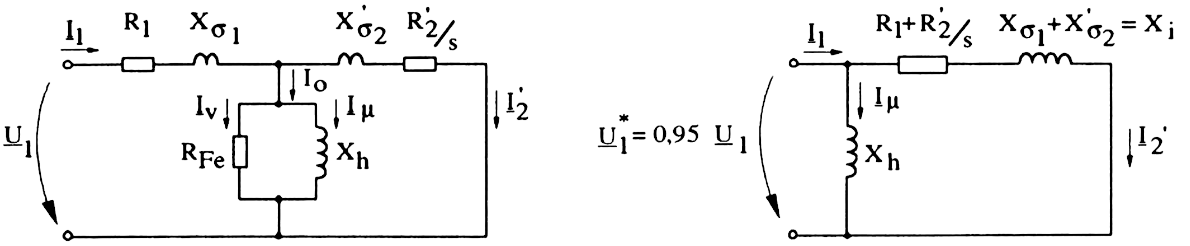


Figure 16 (complete simplified equivalent circuit for the asynchronous motor)

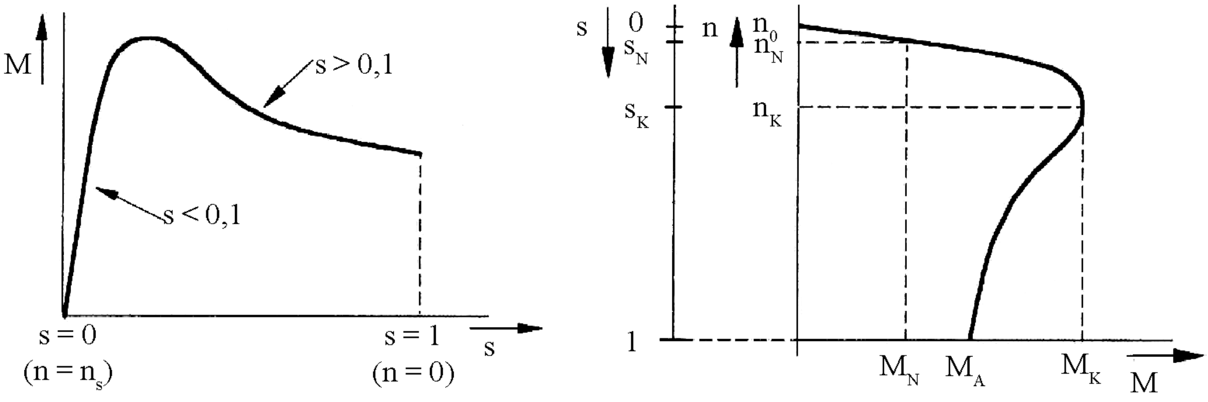
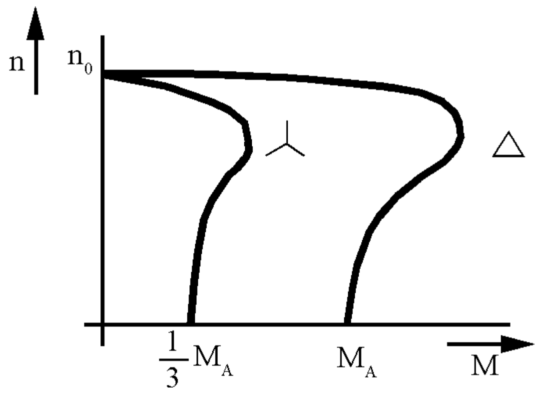


Figure 17

Figure 17 shows the typical response curve of an industrial motor which runs at fixed frequency. If, in this example, breakdown (or stalling) torque Mk is exceeded, then the machine will „pull out" or become unstable and the current will rise abruptly (short circuit). This behaviour cannot be prevented by a frequency converter if this controls (i.e. open loop control) only the frequency and voltage proportionally. If, by contrast, one uses a frequency inverter which regulates (i.e. closed-loop control) the motor by way of current-regulated field orientation, then the motor`s „pulling out" will be avoided (this will be discussed in the section on field orientation). Where no frequency inverter is used, the switch-on current and the start-up torque can be optimised by applying two tricks. In the star-delta circuitry of certain industrial motors the coils are designed so that the initially draw rated voltage in the delta circuit. Then, in compliance with the formula we know, we actually have about 296 V of the 400 V in the star circuit.
If one now applies a voltage of just 400 V to this star circuitry, then the value for the current will not rise so sharply and the machine can run up to speed – at least at a no-load condition:



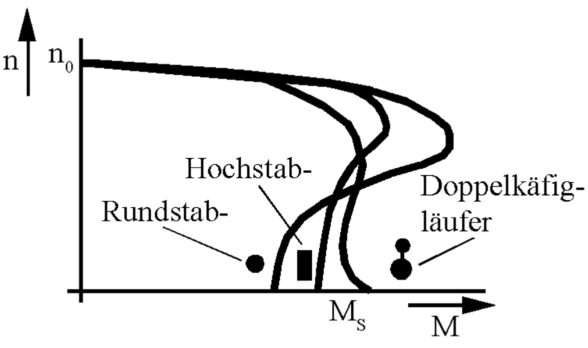
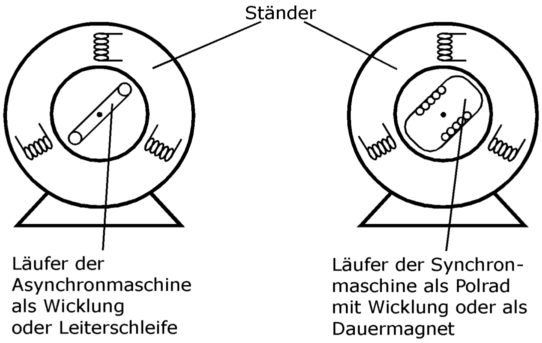


Figure 18 shows the start-delta run-up curve for an industrial motor and, in the adjacent diagram, the difference between the „hard" industrial motor (round-bar rotor), the „soft" elevator motor used with thyristor voltage dividers (realised using a double cage, for example), and the „medium-hard" elevator motor designed to be powered with a frequency converter (deepbar rotor).
As an attentive reader you will be wondering why the normal industrial motor is not used, in conjunction with the frequency converter, in elevator drive operations. The only reason is the noise. Noise is the mortal enemy of every lift and an industrial motor is „bred" for maximum performance at the smallest possible physical size. A modern elevator motor should also strive for this ideal but the high power density involved forces the manufacturer to run the motor very close to its magnetisation boundary (saturation). The laminated iron core, when saturated, results in the typical torque howl when the motor is heavily loaded. A „soft" motor will enter the saturation state far later and thus tends to be quieter. The modern lift motors consequently contain a little more iron (the coil design is selected so that the iron will not be fully utilised) and under certaincircumstances will feature a slightly larger air gap or a rotor with a tendency to deepbar design. Also proven to be highly effective as a further noise-abatement measure is using the grey casting as the housing instead of the extruded aluminum section which is standard for industry applications. If, in addition, a harmonic PWM process is selected for the frequency inverter along with feedback using the since/cosine rotation value transducer (1 Vpp technology), the motor will run extremely quietly. In contrast to the asynchronous motor, the synchronous motor has a rotating permanent magnet rotor or a rotor to which outside energy is applied by way of slip-rings.
The permanently excited, outside-rotor synchronous motor is much favoured today for small and medium-sized gearless winches. Asynchronous motors with a high number of poles and/or running at low frequencies are used in gearless winches only at higher

payloads. The reason is that it is difficult to manufacture the strong permanent magnets required here.
Asynchronous gearless drives are in fact economical in their manufacture but have an unfavourable size and/or shape for smaller payloads and in designs without a separate machinery room. Thus the synchronous motors with planetary gearing are given preference. The difference between asynchronous and synchronous designs is shown in **Figure 19**.



A very important distinction between asynchronous and synchronous motors is that the attitude of the magnet wheel will have to be known when switching on the synchronous motor since there could otherwise be a very sharp switch-on jerk (rotor latching torque). To ensure that this cannot happen, these synchronous motors are equipped with a special rotation angle transducer system. The position of the magnet wheel is, in the simplest case in for very small servomotors, determined with Hall sensors (typical for trapezoidal commutation) and in larger servomotors using resolvers (typical since commutation). In the elecator field very slow-running synchronous motors are used. These motors must be engineered at very high quality; here Hall sensors and normal resolvers will no longer be sufficient to determine he positions of the pols along the magnet wheel. As a rule, genuine absolute value transducers with an SSI interface will be employed. There are actually two transducers in one housing. In addition to the 13-bi, single-turn, absolute position value transducer, there is a 1 Vpp sine/cosine trace with (typically) 2048 increments per motor revolution. The 13-bit attitude signal – one it has been calibrated – will forwarded to the frequency inverter as the „second transducer". Normally the system will read in only one time at the start; then the real-time value is derived from the 1 Vpp trace by way of interpolation.
The trend toward gearless concepts means that both the frequency inverter (indispensable in this case) will have to be of extremely high quality in regard to their regulation properties. Motor manufacturers must active extremely exact geometry in the execution of the stator and the rotor. Any tolerances in the air gap, in grooving location (angled grooves are obligatory) and in the winding of the coils will result in rougher running, increased noise generation and heavy vibrations. As regards the regulations unit, current controlled field orientation is the state of the art. This will be used in both asynchronous an synchronous motors. The only difference here is hat the asynchronous machine requires calculations of slip frequency by means of a very complex vector transformation while a slip angle is calculated for the synchronous unit, In Figure 20 we see high-Quality field orientation. The purpose of field orientation is that the 3-phase system be calculated back to the DC system an vice course. In this way we once again attain two magnitudes designated ISD (field current) and ISQ (armature current), which we met in the section on the DC motor. We will, in principle at least, find all the parts of our DC motor in the field orientation concept. The inverse transformation (shown as an option in the illustration) has, for example, the same task as the compensation coil in the high-value DC motor. If one now replaces the actual ISD set-Point value or the actual ISQ value with the ISD set-point value, then the field orientation is simplified through the inverse transformation. The disadvantage is that rotor time constants an rotor flux will

not be corrected to follow rising motor speed (the excitation of the motor drops off more sharply than what is actual desirable).
The heart of field orientation is represented by two parameters: the rotor flux determines the values of ISD; ISD is equivalent to the field in the motor. ISD is regulated so that motor excitation is kept constant through to the nominal working point. Only when the nominal working point is exceeded will ISD be run down in accordance with the curve which characterise iron. Thus a field attenuation is set up which makes it possible, a least theoretically, to operate this motor at up to 4 to 6 times its rated speed (torque quickly goes to zero, however, since the friction an losses in the motor become too great). Field attenuation is not advisable in elecator operations; it should be a maximum of 5% above the nominal working point. In synchronous motors with permanent excitation field attenuation is not possible in any case and is associated with undesired reactive power.
The decoupling of the virtual ISD and ISQ currents determines the rotor time constants. The following relationships apply: If the cosine-phi value for the motor is low, then the rotor time constants will be small and slip will be large. Consequently old elevators exhibit values between 40 and 150 ms (cosine-phi of 0.60 to 0.75). New elevator motors, by contrast, exhibit values of between 40 and 150ms (cosine-phi of 0.75 to 0.85). Industrial motors lie in a range of from 200 to 600 ms (cosine-phi of 0.8 to 0.95). These comments apply to motors of medium power (5.5 to 55 kW). The optimal value is the one at which the lowest possible load current flows.

3. Field-oriented regulation in elevator technology

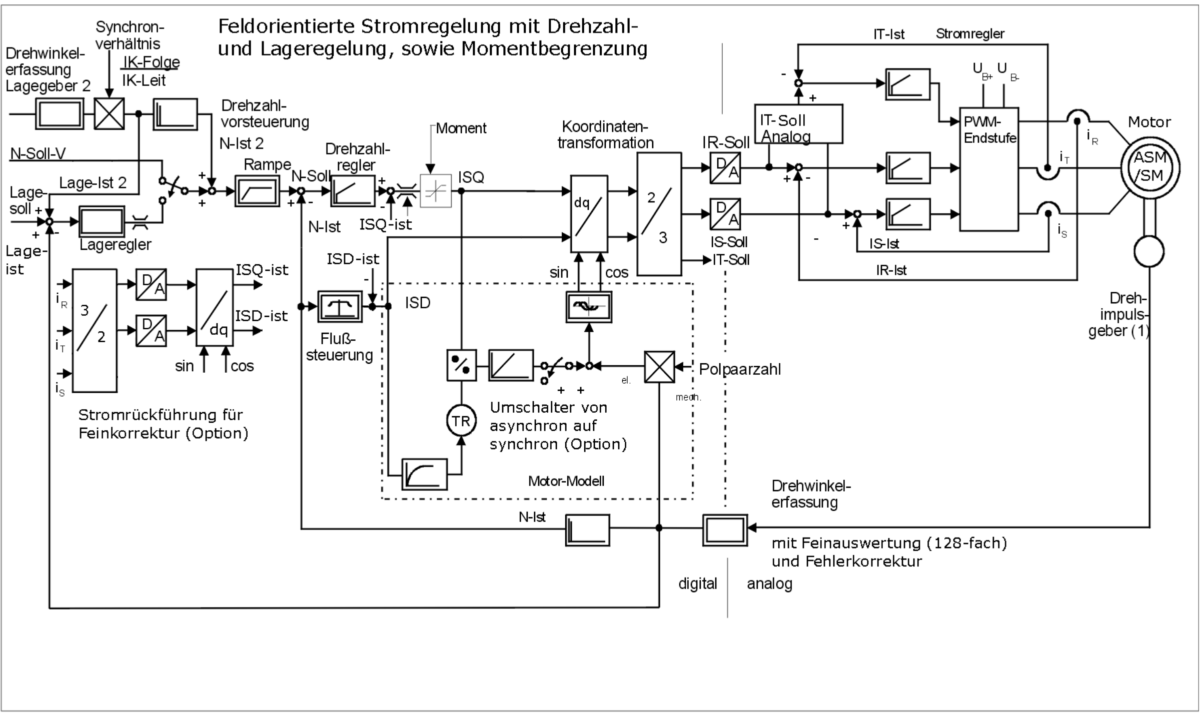


Figure 20 shows the flowchart for field orientation working in the asynchronous/synchronous mode.

In the DC machine, which is easy to explain mathematically, the commutator ensures that the field at the armature is nearly perpendicular to the field for the exciter coil. The formula here is Mi=cxΦ x Ia (see also the comments on the DC motor). As regards the asynchronous motor this is Mi=cxΦxI2 (where I2 is to be the motor current). In Figure 16 and at a no-load situation, I1 and In are identical in value and the current I2 in this case is zero.
Only when placed under load will the rotor turn until the counter-torque has been established. The task to be carried out by field orientation is now to make available – in a fashion similar to a DC motor – current forming the field and the current developing the torque.
A typical asynchronous motor with three windings located spatially at offsets of 120 degrees will be fed with three sine currents also offset by 120 degrees through time; thus every current in the coils generates a magnetic field. If one were to consolidate these three magnetic fields, then the field which resulted could be depicted with just one single flow indicator.

With the registration of the three stator currents and simultaneous scanning of the transducer signal (1 Vpp x 128-fold multiplication with adaptive error correction) a transformation will be made in the a-ß coordinate system. Here one attains a rectangular coordinate system oriented on the stator. These components are variable magnitudes in each coordinate system.
The current indicator rotates within the motor. We want to decouple the components of the current indicator which form field an those which form torque. That is why a further transformation is made in the d-q coordinate system. In these coordinate systems, synchronous to the field, there arise two separately controllable components – the ISD components for the field and the ISQ components for torque.
These two controllable components are passed through a model of the asynchronous motor so as to optimise the associated flux value and the associated slip frequency. Using these newly calculated values, an inverse transformation will be carried out using a so-called vector rotator. The newly derived output values for the current controller are converted into the corresponding voltages and the function of the power inverter is to impress them upon the current. Required for ideal field orientation are not only exact alignment of the motor model with the asynchronous motor itself; also required are an adaptive speed controller as wall as an attitude controller as a zero-point controller. Values with this degree of technical excellence are offered by only a few manufacturers.