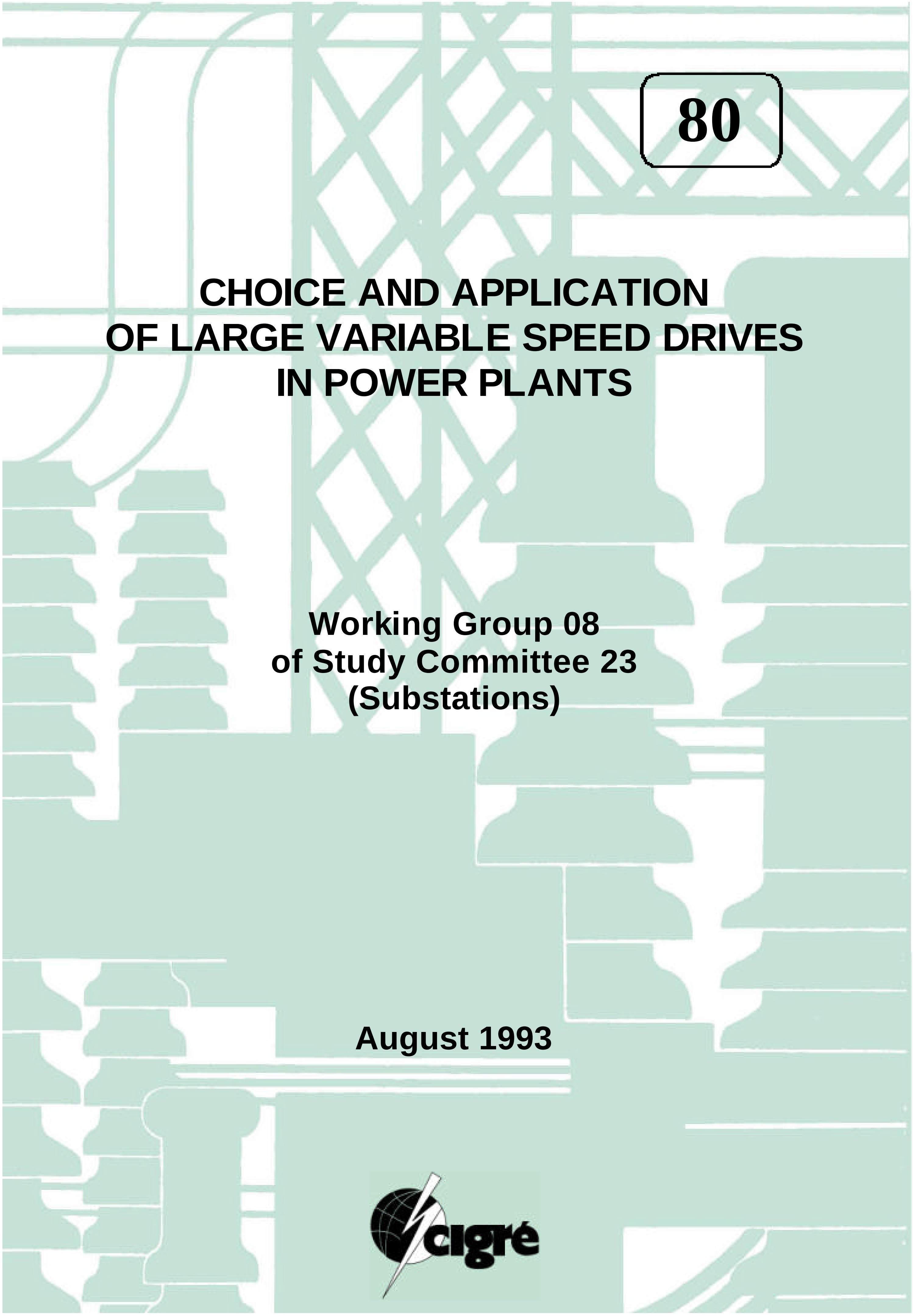

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CHOICE AND APPLICATION OF LARGE VARIABLE SPEED DRIVES IN POWER PLANTS

Working Group 08
of Study Committee 23
(Substations)

August 1993

[22] ETG-Fachberichte, Nr. 17, Netzrückwirkungen,
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[23] Netzrückwirkungen von Drehstromantrieben mit
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ELEKTRIE, Berlin 39 (1985)

[24] Stromrichter-Netzrückwirkungen
Dipl.-Ing. M. Clemens, AEG Berlin

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Siemens-Publication Nr. A 19100-E314-A308-X-7600

1. General

This report has been prepared at the request of the Chairman of Cigre Study Commitee 23 and deals with the subject "Choice and Application of Large Variable Speed Drives in Power Plants".

The work started within Working Group 23-06 which is now known as Working Group 23-08.
At the first meeting of Working Group 23-08, held in Arnhem in April 1989, a draft report was discussed. Several suggestions were made for scope and improvement. Among other things the members decided to add variable speed drives which employ variable speed couplings.

The object of this report is to document the extent of application of variable speed drives in existing power plants, to review the considerations leading to their choice and to give recommendations for applications. Variable speed drives with steam turbines are not considered.

In 1991 a questionnaire (Appendix 1) was prepared and circulated to the members of Working Group 23-08 and Study Commitee 23 to gain additional information for completion of the report and for improvement of the analysis.
The questionnaire was answered by Australia, Canada, Belgium, Denmark, France, Germany, Italy, Japan, Norway, The Netherlands, Switzerland and United Kingdom.
The results of the questionnaire are annexed (Appendix 2). Though it is not easy to give exact data, the questionnaire concludes, that variable speed drives have so far had limited application in power plants.
The answers initially referred to variable speed drives higher than 500 kW.
Subsequently the Working Group decided for completeness of the report to include variable speed drives higher than 200 kW.

2. Introduction

New methods and technologies, larger units to raise productivity and economy, e.g. in the chemical industry, in the iron and steel industry and in power plants, continually necessitate larger driving units. Because the electric drive is specially suited to meeting complex control requirements, more and more large electric drives are used. However optimum operating results can usually only be obtained, if large drives have speed controls. Modern semiconductor techniques facilitate the speed control of induction motors. The driving characteristics such as control range, control precision, dynamics, efficiency and multi-quadrant operation are marginally better than in the case of d.c. drives. Other advantages of induction motors therefore become more important, i.e. high robustness, high reliability, low maintenance and high power ratings. With regard to achievable power and speed, variable speed a.c. drives cover ranges which are outside the capability of d.c. drives. D.c. motors are limited in power and speed by their commutation requirements.

This report surveys all practicable types of electric drives of large power (>200 kW) and their variable speed control systems, as applied in the past and as used today. Chapter 7 gives recommendations and advice to be considered in applying variable speed drives in new power plants. For greater ease and flexibility in process control, possible savings in operating expenses and the virtual elimination of maintenance, electronic power convertors are preferred for controlling and adjusting the speed of large motor drives in power plants. If convertors are used concerns with respect to harmonics and other effects in the power supply systems must be taken into consideration.

Other methods for varying the speed of large motor drives are available which do not use convertors, e.g. the application of variable speed couplings (chapters 5.3 and 6.2).

In this report the drive is considered as a system with system properties and system performance. The report does not deal separately with details of electric machines or convertor equipment. These separate aspects have already been considered by Study Commitee 11 [1].

Standardised terms according to IEC-Publication 50(551) habe been used [2] (e.g. convert<u>o</u>r etc.)

3. Choice of large motor drives and methods of speed control

Basically three types of electrical machine are available for driving large pumps, compressors etc.:

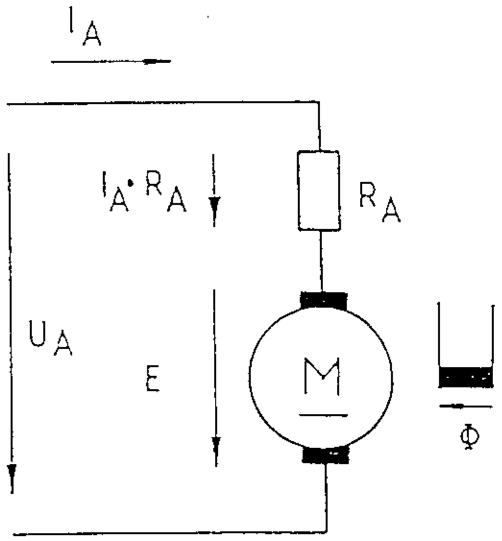
- d.c. motor (chapter 4)
- induction motor (chapter 5)
- synchronous motor (chapter 6)

The various possible methods of speed control are considered for these three types of electrical machine. Possible control/power circuits are described and the advantages and disadvantages are discussed.

4. Drives with d.c. motors

The possibilities for speed adjustment of separately excited d.c. motors are the result of the following motor formulae [3]:

$$
\begin{aligned}
U_A &= E + I_A \cdot R_A \\
E &= C_1 \cdot n \cdot \phi \\
M &= C_2 \cdot \phi \cdot I_A \\
\phi &\sim I_F
\end{aligned}
$$



U_A = armature voltage
E = electromotive force (e.m.f)
I_A = motor current
R_A = internal resistance
C_1, C_2 = machine constants
n = speed
ϕ = flux
M = torque
I_F = field current

Fig. 1: Equivalent circuit of separately excited d.c. motor

For speed adjustment two control variables are usual:

1. Variation of armature voltage (chapter 4.2)

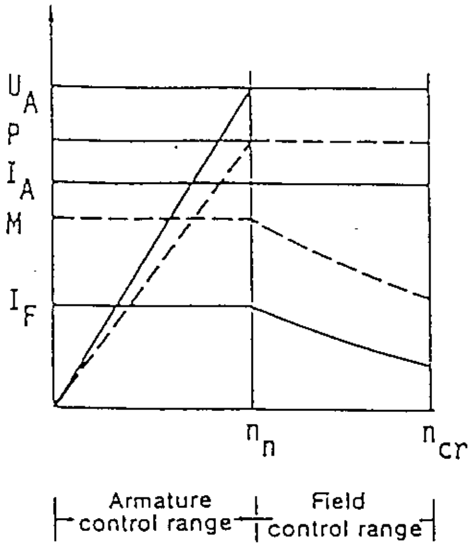
$$n = \frac{E}{C_1 \phi} = \frac{U_A - I_A \cdot R_A}{C_1 \cdot \phi} =$$

$n \sim U_A \quad \phi, M, I_A = \text{const.}$

2. Variation of field current (chapter 4.1)

$$n = \frac{E}{C_1 \phi}$$

$$n \sim \frac{1}{I_F} \qquad M \sim \frac{1}{n} \qquad I_A, U_A = \text{const.}$$



U_A = armature voltage
P = power
I_A = armature current
M = torque
I_F = field current
n_n = base speed
n_{cr} = critical speed, determined by the commutator

Fig 2: Characteristics of separately excited d.c. motor

4.1 D.c. motors with field current variation (field-weakening control)

Where variation of field current with constant armature voltage is employed the drive is particularly simple and low-priced. Only a rectifier with a three-phase bridge connection and diodes in the armature voltage circuit and a half-controllable single-phase bridge connection for field current variation are required (Fig. 3a). However the range of operation in the speed torque diagram is limited (Fig. 3b). Because of the low speed adjustment range (1:3 - 1:5) [3] from the base speed (n_n) to the critical speed (n_{cr}), limited by the commutator, and because of the reduction of motor torque with increasing speed, the d.c. motor with field current variation is not practical. The d.c. motor needs a starter resistor (R_V) [4] for running up.

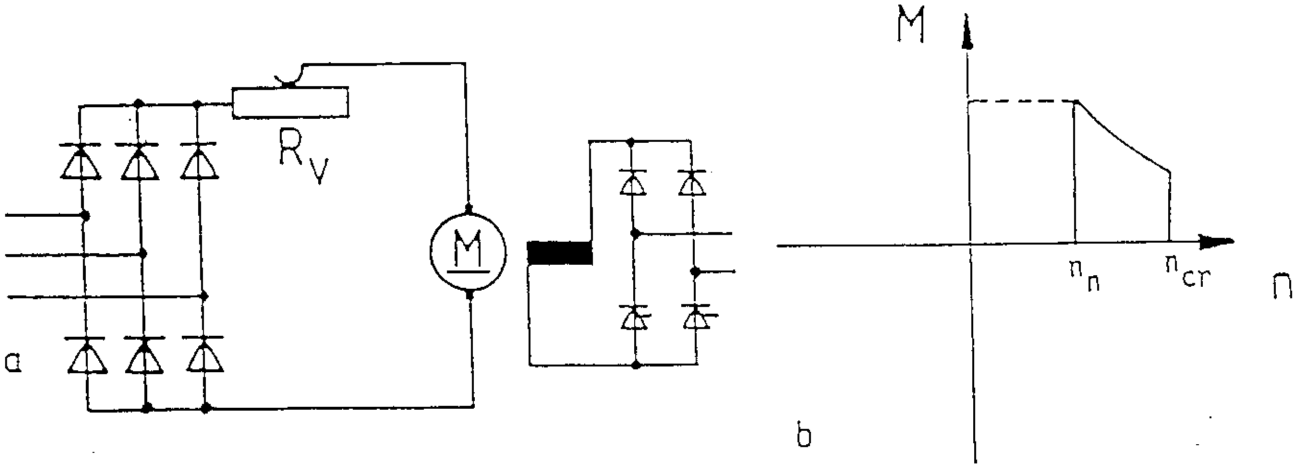


Fig 3: D.c. drive with field current variation
a: circuit diagram
b: speed torque diagram

M: torque
n_n: base speed
n_{cr}: critical speed

4.2 D.c. motors with armature voltage variation

Armature voltage variation requires a controllable three-phase bridge connection in the armature circuit and a non-controllable single-phase bridge connection in the field current circuit (Fig. 4a). The motor torque is constant in the total speed range of armature voltage variation (Fig. 4b).

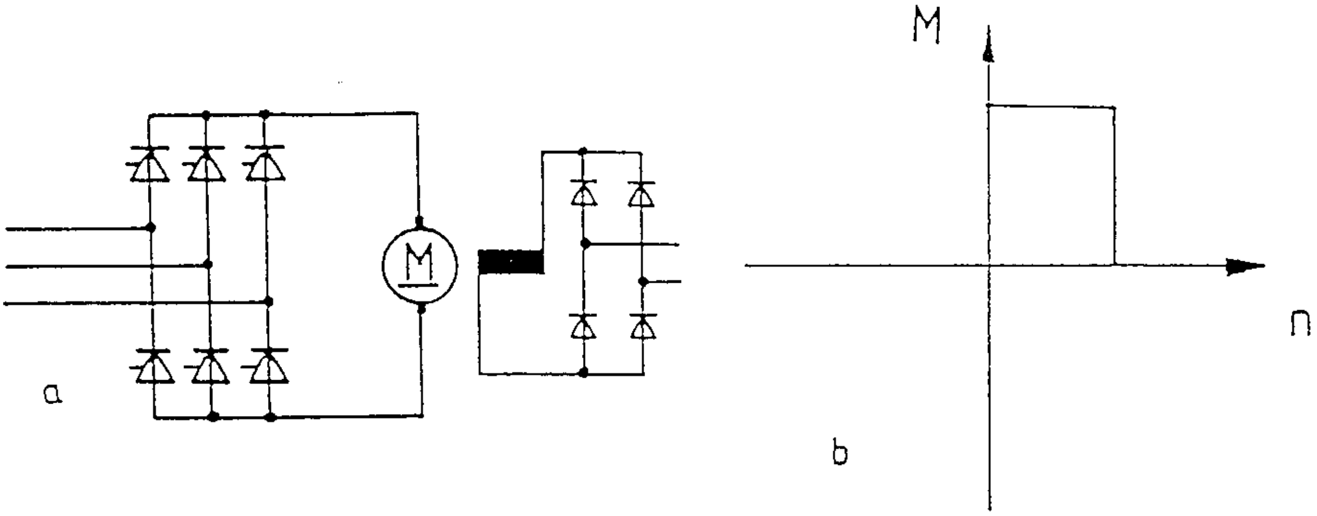


Fig. 4: D.c. drive with armature voltage variation
a: ciruit diagram
b: speed torque diagram

4.3 D.c. motors with armature voltage and field current variation

If the total speed range in the speed torque diagram is needed, armature voltage _and_ field current must both be adjustable.

4.3.1 D.c. drives with Ward Leonard (rotary) convertor

The Ward Leonard convertor is suitable for adjusting and controlling the speed in the total capability range of d.c. motors (Fig. 5). The adjustment of the speed of the Leonard motor by armature voltage variation derives from armature voltage variation of the Leonard generator. Operation in the field-weakening range is possible by varying the field current of the Leonard motor.

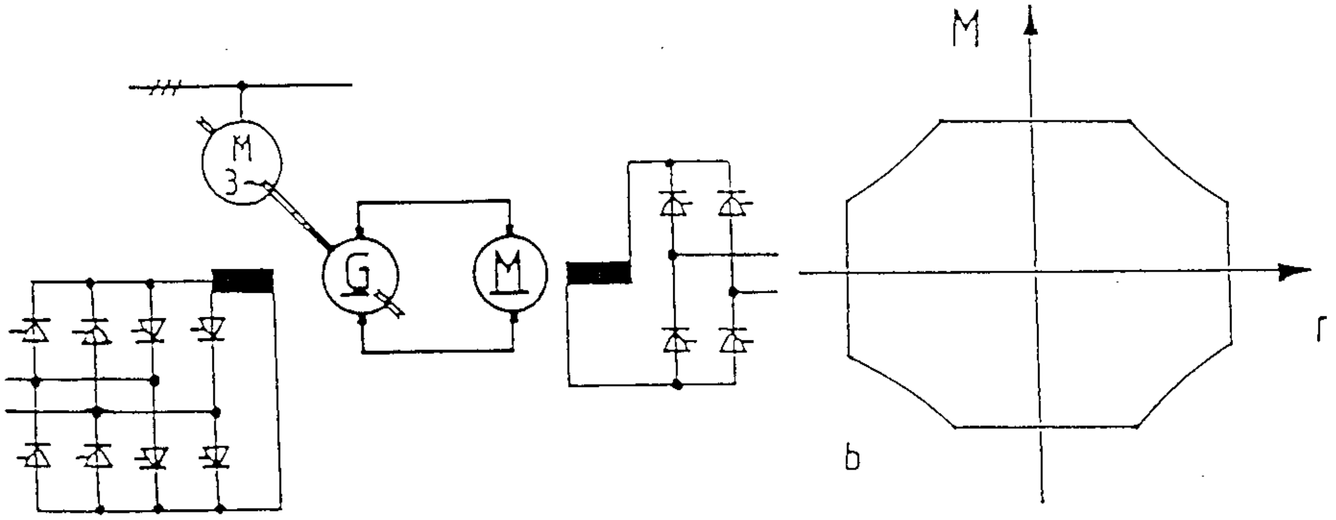


Fig. 5: D.c. drive with Ward Leonard convertor
a: circuit diagram
b: speed torque diagram

Since static (electronic) convertors of large power rating have become available, the Ward Leonard convertor is seldom used due to its low efficiency, the necessity for additional floor space, increased maintenance and poor dynamic response. A static convertor feeding the armature circuit of the d.c. motor has replaced the Ward Leonard motor-generator set.

4.3.2 D.c. drives with static convertor feed

For reversible speed control reversible convertors (double convertors) are applied, permitting multi-quadrant operation similar to Ward Leonard convertors (Fig. 6). However d.c. drives with static convertor feed have superior efficiency and dynamic response.

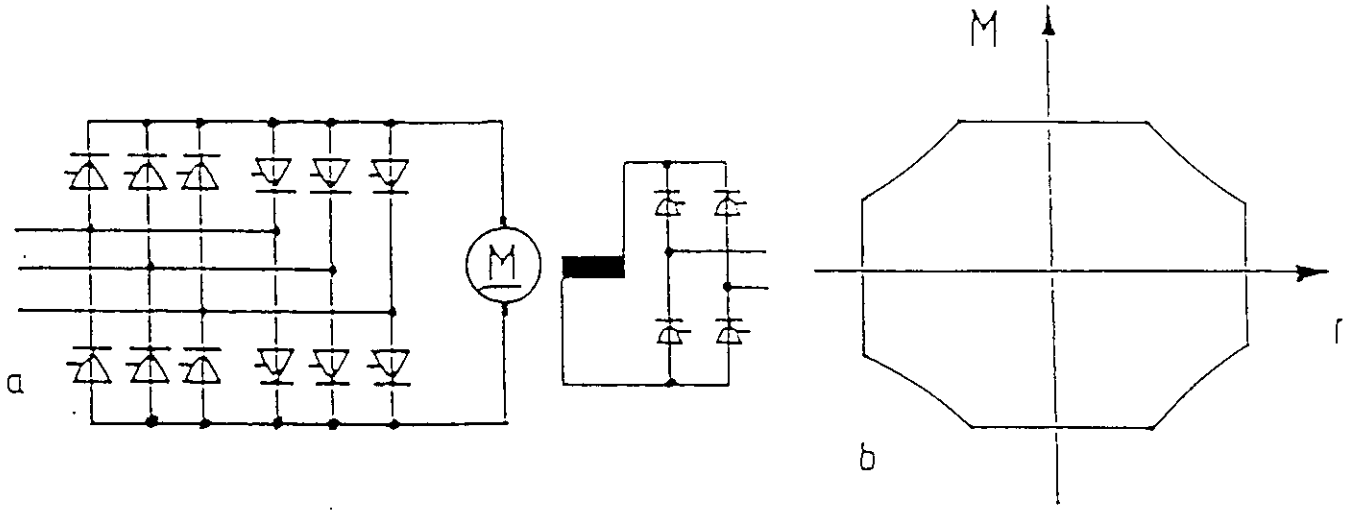


Fig. 6: D.c. drive with static convertor feed
a: circuit diagram
b: speed torque diagram

If one quadrant operation only is required, (e.g. in the case of pumps or fans) a simple convertor for the armature circuit is sufficient (Fig. 7).

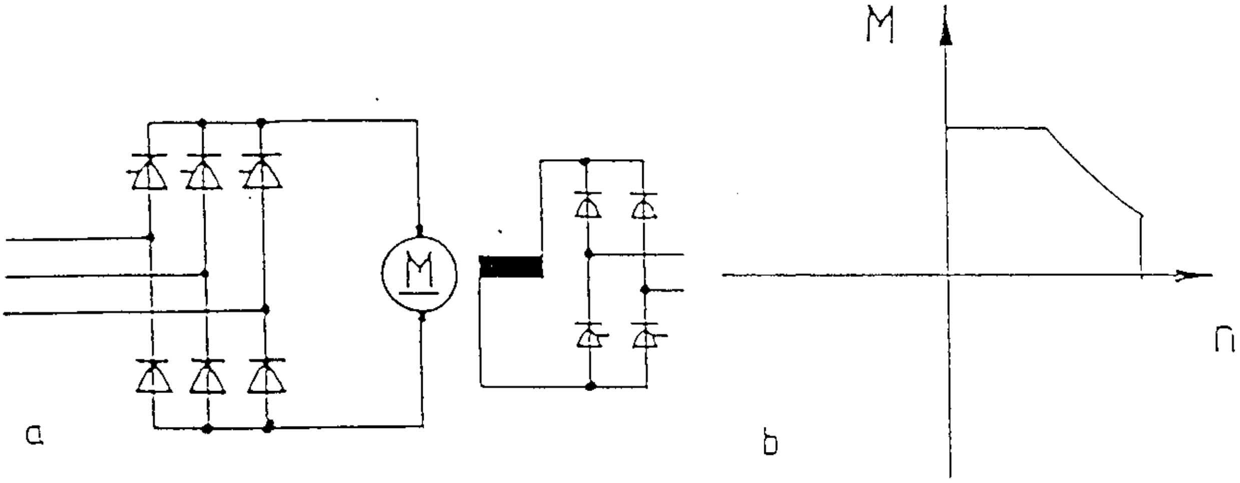


Fig. 7: D.c. drive with armature circuit convertor
a: circuit diagram
b: speed torque diagram

5. Drives with induction motors

The induction motor is the most commonly used electric machine. For reasons of simple design and construction and therefore high robustness, low maintenance and low price the induction motor is applied to large drives with speed control in many branches of industry.

The possibilities for speed adjustment of induction motors derive from the following motor formulae [5]:

$$n = \frac{f}{p}(1-s)$$

$$s = \frac{n_s - n}{n_s}$$

n = speed
f = stator frequency
p = number of pairs of pole
s = slip
n_s = synchronous speed

For speed adjustment the following variants are possible [6]:

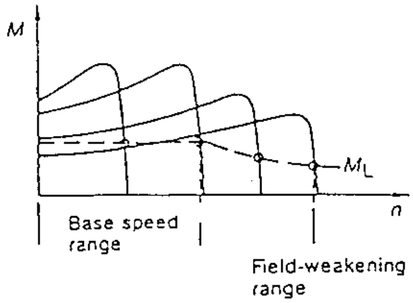
1) stator frequency variation (Fig. 8)
2) slip variation
    2.1) rotor resistance variation (Fig. 9)
    2.2) stator voltage variation (Fig. 10)
    2.3) rotor voltage variation (Fig. 11)
3) pole switching (Fig. 12)

Stator frequency variation is the variant with lowest losses and highest variable speed range. Constant motor torque requires adjustment of the stator voltage in proportion to stator frequency by reference to the following formulae:

$$M \sim \phi \cdot I_2$$

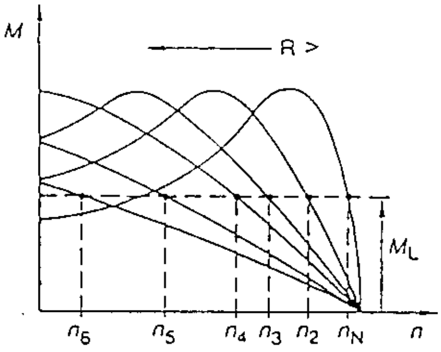
$$\phi \sim \frac{U}{f} = \text{const.}$$

M = torque
U = stator voltage
f = stator frequency
φ = machine flux



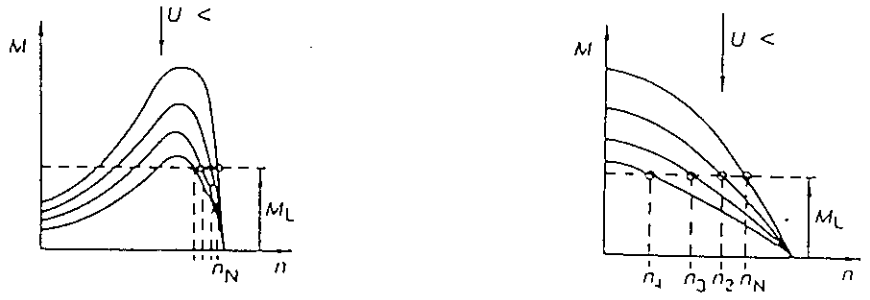
M_L = load torque of the driven machine

Fig. 8: Speed torque diagram of an induction motor at various values of stator voltage and frequency (variant 1)



R = rotor resistance
n_N = rated speed

Fig. 9: Speed torque diagram of an induction motor at various values of rotor resistance (variant 2.1)



without extra rotor resistance

with extra rotor resistance

Fig. 10: Speed torque diagram of an induction motor at various values of supply voltage (variant 2.2)

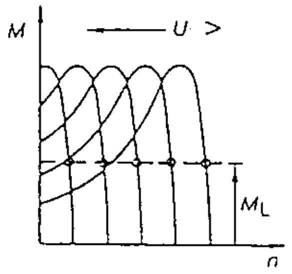


Fig. 11: Speed torque diagram of an induction motor at various values of rotor voltage (variant 2.3)

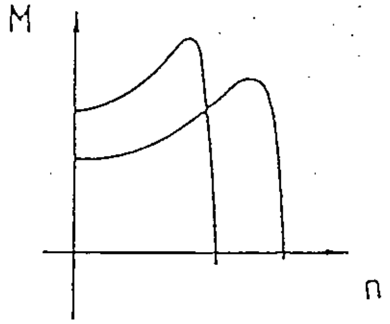


Fig. 12: Speed torque diagram of an induction motor with pole switching (variant 3)

5.1 Induction motor with squirrel-cage

5.1.1 Speed control by pole switching

If three-phase squirrel-cage motors have several stator windings, it is possible to adjust the speed in steps by pole switching (Fig. 13) (i.e. switching from one stator pole configuration to another).

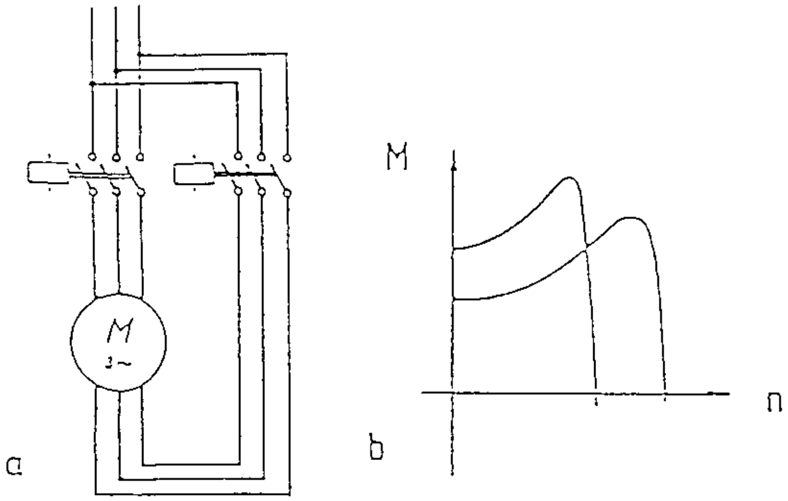


Fig. 13: Three-phase squirrel-cage motor with pole switching
a: circuit diagram
b: speed torque diagram

Drives with pole switching are a low price solution for speed control where 2 to 4 speed adjustment steps are sufficient, e.g. in the case of simple pumps and fans [4].

5.1.2 Speed control by stator voltage variation (three-phase a.c. power controller)

The speed control of squirrel-cage induction motors is possible in a limited range by adjustment of stator voltage at constant frequency. A three-phase a.c. power controller is suitable for adjusting the stator voltage continuously.

For lower speeds the motor operates in a higher slip range. Hence, the rotor losses increase and the level of efficiency decreases. The torque is approximately proportional to the stator voltage squared.

Because of the high losses three-phase a.c. power controllers are used in a power range up to 100 kW only, and in a limited speed range (Fig. 14). Three-phase a.c. power controllers are applied to crane equipment and small hoists [4].

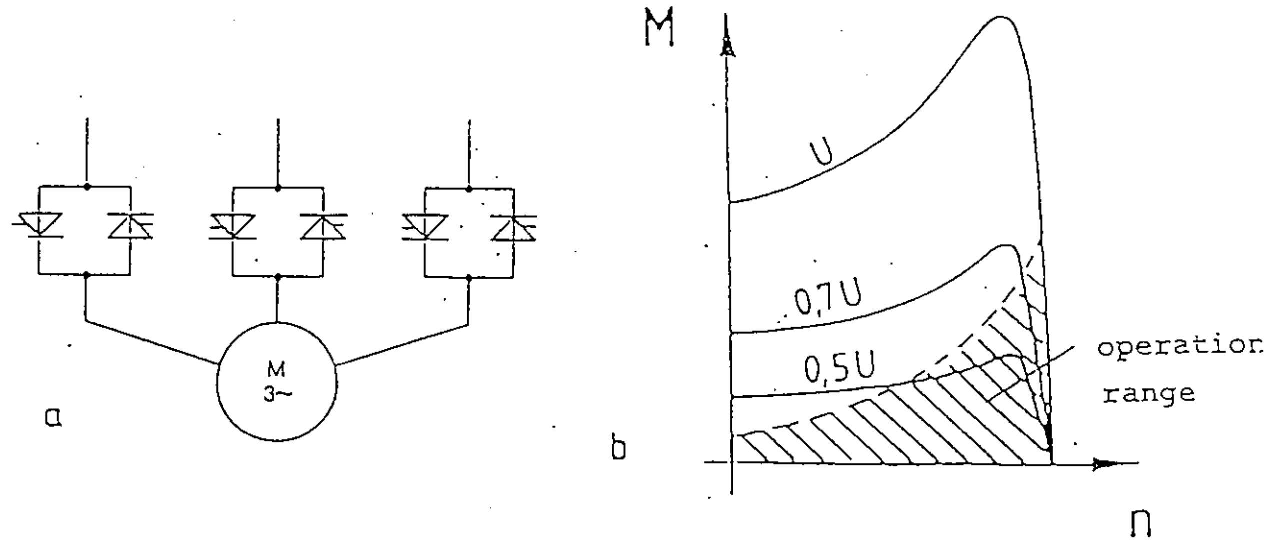


Fig. 14: Three-phase a.c. power controller
a: circuit diagram
b: speed torque diagram

Another application of the three-phase a.c. power controller is for reduction of current and torque in the starting of induction motors with squirrel-cage. This so called "motor soft-starting" equipment is available in a power range up to 1250 kW [7].

5.1.3 Speed control with static frequency convertor

By adjusting frequency and supply voltage (in proportion) by means of frequency convertors any operating point in the speed torque diagram is permissible and provides low-loss operation.

It is possible to raise the motor supply frequency higher than the source (or line) frequency for increasing speeds, provided higher speeds are permissible for the mechanical components.

Two convertor arrangements are used:

- direct a.c. convertor
- indirect a.c. convertor

5.1.3.1 Direct a.c. convertor (cyloconvertor)

A direct a.c. convertor is an a.c. convertor which employs no energy storage, i.e. without a d.c. link (Fig. 15) [6].

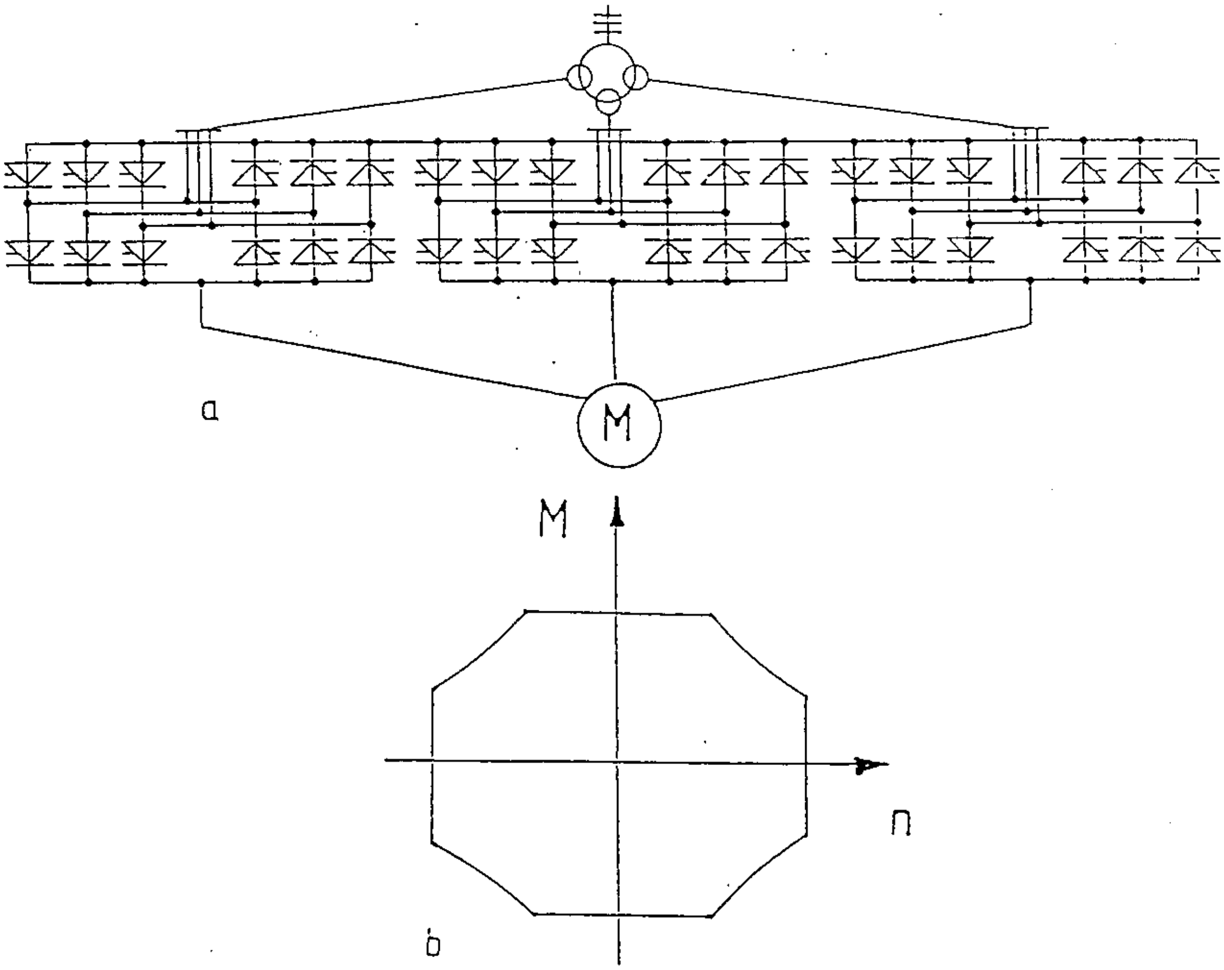


Fig. 15: Induction motor with direct a.c. convertor
a: circuit diagram
b: speed torque diagram

Direct a.c. convertors can be used for applications where the required output frequency does not exceed approximately 0.5 times the input frequency. For adjusting speed the stator frequency and the stator voltage are varied by controllable, line-commutated convertors. A direct a.c. convertor consists of 3 reversible convertors in a circulated current-free anti-parallel connection, which are monitored in such a way that the induction motor receives a three-phase voltage of the desired frequency and phase. Induction motors with direct a.c. convertors are suitable for multi-quadrant operation and allow adjustment of speed down to zero r.p.m. with high torque. The control dynamics correspond to those of d.c. drives with reversible convertors.

Direct a.c. convertors are applied for drive power ratings in the megawatt range and speeds below a few hundred r.p.m., e.g. for rolling mill main drives, mine winders and grinding mills [8].

5.1.3.2 Indirect a.c. convertor

An indirect a.c. convertor is an a.c. convertor with a d.c. link.

For indirect a.c. convertors the frequency transformation is achieved in 2 steps, i.e. by a line-side rectifier and a load-side inverter, which are connected by an interposed d.c. link containing smoothing elements such as capacitances or inductances.

Two variants are applied depending on whether the d.c. link produces a load-independent voltage waveform or a load-independent current waveform [6]:
- voltage source d.c. link convertor and
- current source d.c. link convertor.

5.1.3.2.1 Voltage source d.c. link convertor

5.1.3.2.1.1 Voltage source d.c. link convertor with variable d.c. link voltage

The line-side, controllable, line-commutated convertor generates a variable d.c. voltage from the line voltage. This is smoothed in the d.c. link using a capacitor. The motor-side convertor generates a three-phase variable voltage at variable frequency from the variable d.c.

voltage. It consists of three inverter phases, each having 2 power transistors or GTO (gate turn-off) thyristors in series, and diodes in an anti-parallel connection (Fig. 16).

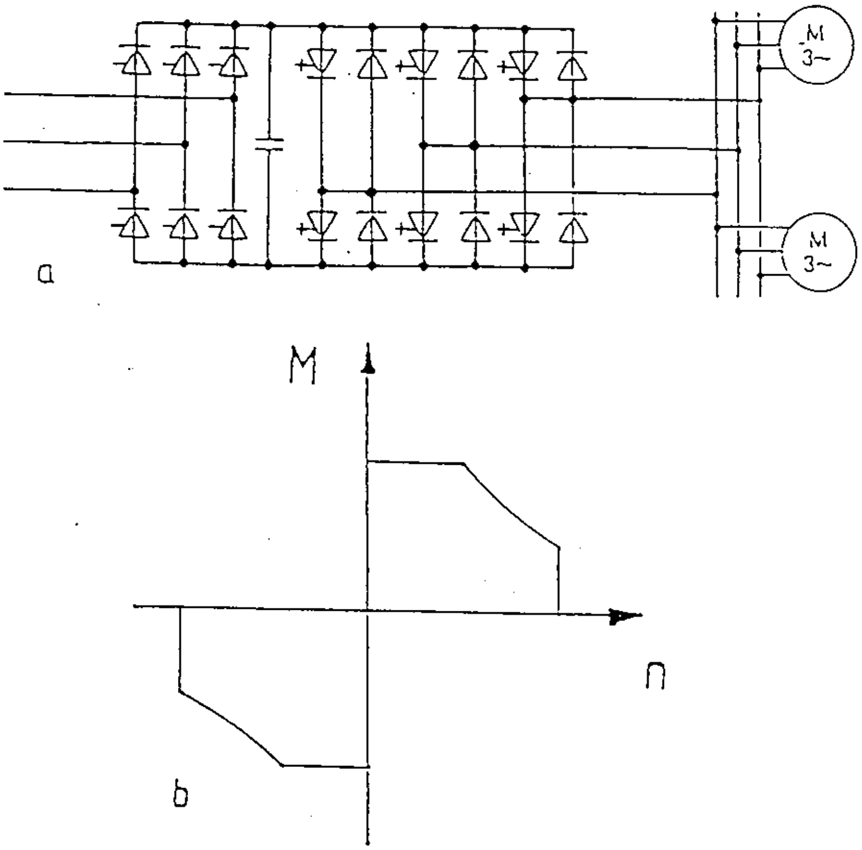


Fig. 16: Induction motor with voltage source d.c. link convertor and variable d.c. link voltage
a: circuit diagram
b: speed torque diagram

At present voltage source d.c. link convertors with variable d.c. link voltage are available up to a power rating of approximately 350 kW, an output frequency of about 400 Hz and a typical speed range of 1:10. This convertor type enables two quadrant operation without braking and is essentially used for multi-motor drive applications. For multi-quadrant operation a reversible convertor is required on the line side (Fig. 17) [9].

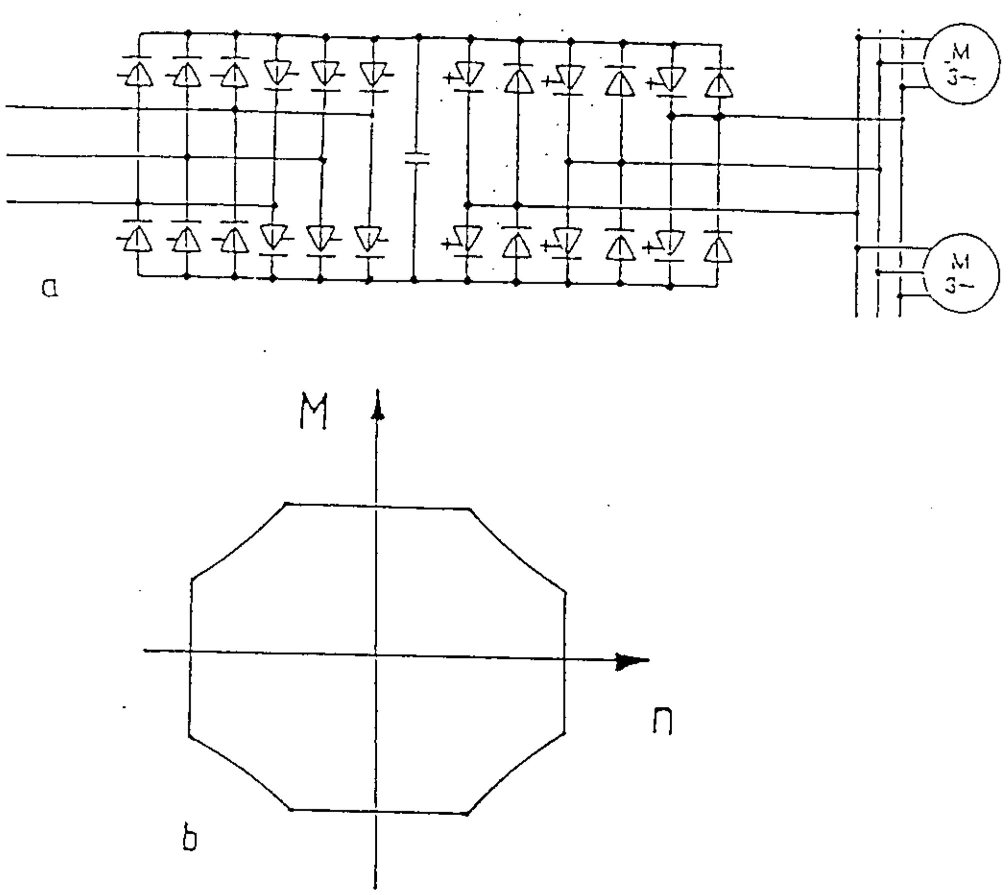


Fig. 17: Induction motor with voltage source d.c. link and variable d.c. link voltage for multi-quadrant operation
a: circuit diagram
b: speed torque diagram

5.1.3.2.1.2 Voltage source d.c. link convertor with constant d.c. link voltage

This convertor consists of a non-controllable, line-commutated convertor, a constant d.c. link voltage with d.c. link capacitors connected in turn to an inverter with pulse-width modulation (PWM-inverter) (Fig. 18). It generates a three-phase voltage at variable frequency and amplitude from the d.c. voltage using sine wave-modulated pulses at a high frequency.

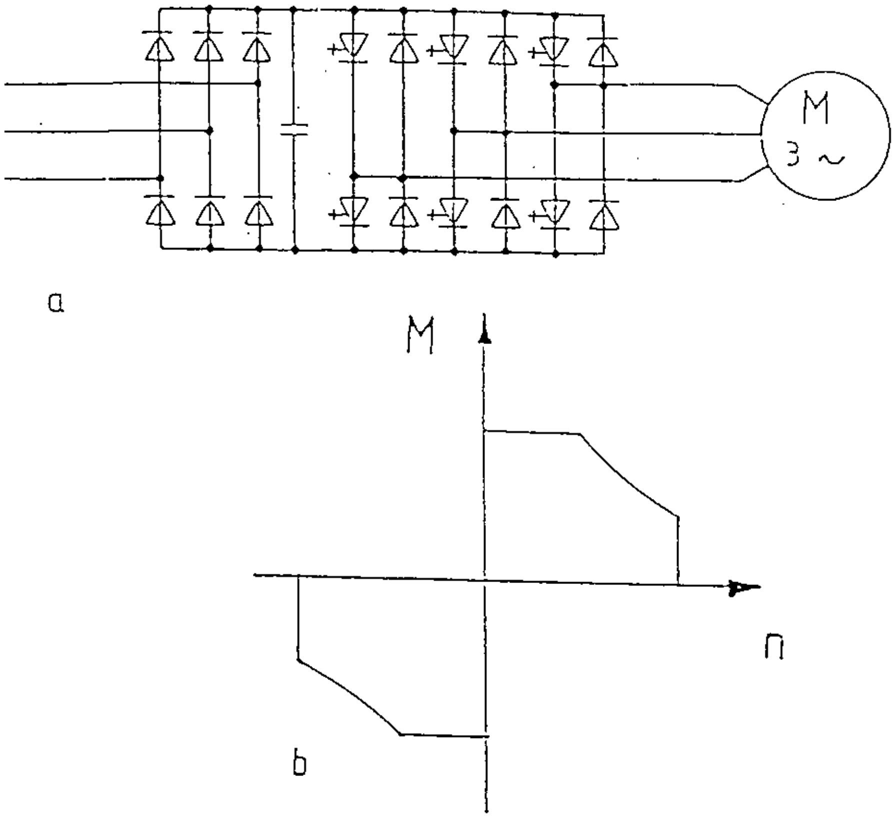


Fig. 18: Induction motor with d.c. link convertor with constant d.c. link voltage
a: circuit diagram
b: speed torque diagram

The inverter has 3 phases. Each of the 3 inverter phases is made up of 2 series-connected power transistors or GTO thyristors and diodes in an anti-parallel connection. The inverter phases represent electronic switches, so that the output terminals of the convertor are alternately connected to the positive and negative side of the d.c. link. Hence, the signals controlling the inverter phases allow the voltage as well as the frequency to be continuously adjusted from zero to the rated or maximum values. Pulse convertors offer excellent dynamic capabilities. The high pulse frequency guarantees a motor current of minimal harmonics, low noise, low motor losses and good rotational accuracy down to the lowest speeds.

On the other side an important aspect must be considered in the case of pulse convertors. The pulses are reflected at the motor terminals dependent on the inverter output pulse rise time and the cable length from inverter to motor and therefore hazardous for motor insulation (voltage amplitudes up to ten times of the terminal voltage). Because the level of motor insulation is normally standardized and the pulse rise time is fixed by the sort of used transistors or thyristors, the cable length between convertor and motor must be minimized. For those situations where the cable length cannot be sufficiently reduced, filters or similar devices must be used.

Today pulse convertors are available up to a power rating of 8 MW, an output frequency of about 200 Hz with a typical speed range up to 1: 200 [10, 11].

5.1.3.2.2 Current source d.c. link convertor

The current source d.c. link convertor consists of a controllable, line-commutated power rectifier, a d.c. link with a smoothing reactor and a self-commutated inverter on the load-side using the phase sequence commutation principle, with thyristors, commutating capacitors and blocking diodes (Fig. 19) [12].

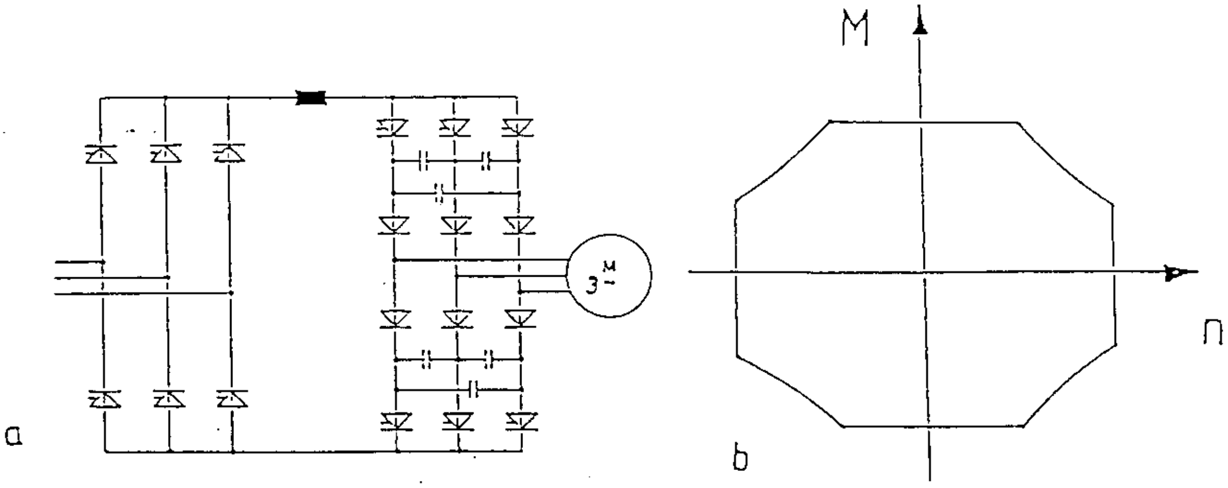


Fig. 19: Induction motor with current source d.c. link convertor
a: circuit diagram
b: speed torque diagram

The power rectifier is controlled, so that a constant d.c. current is produced equivalent to the required motor torque. The inverter switches the d.c. current to the motor phases as 120° square-topped pulses with the desired frequency.

The convertor has the advantage that the control system can reverse the d.c. link voltage polarity for reversal of the energy flow. The line-side convertor switches to inverter operation to feed back the braking energy into the supply system. Multi-quadrant operation is possible without using any extra equipment.

Induction motors with current source d.c. link convertors are robust and low maintenance drive systems with a power rating up to about 3 MW, an output frequency of about 135 Hz and a typical speed range up to 1:20. The current source d.c. link convertor is typically a single drive. Constant operation in low speed range is not possible [10].

5.2. Induction motor with sliprings

The three-phase wound rotor motor permits speed control by addition of an external regulating resistor or a variable electromotive force (e.m.f.) in the rotor circuit.

For operating at maximum speed the sliprings are short-circuited. In this case the three-phase wound rotor motor works like a three-phase squirrel-cage motor.

The three-phase wound rotor motor is more expensive and because of its brushes is less robust than a three-phase squirrel-cage motor. It is also more sensitive to vibration, moisture and dust and needs more maintenance.

5.2.1 Three-phase wound rotor motor with regulating resistor in the rotor circuit (Fig. 20)

Liquid starters are often used as variable regulating resistors. By varying the depth of immersion of the starter electrodes in saltwater, the speed of the wound rotor motor is continuously adjustable.

At constant torque the resistor losses are proportional to rotor slip, resulting in high losses at low speed. These losses require a special cooling system for the saltwater in the liquid starter on large drives. The regulating resistor is used also for limiting the starting current.

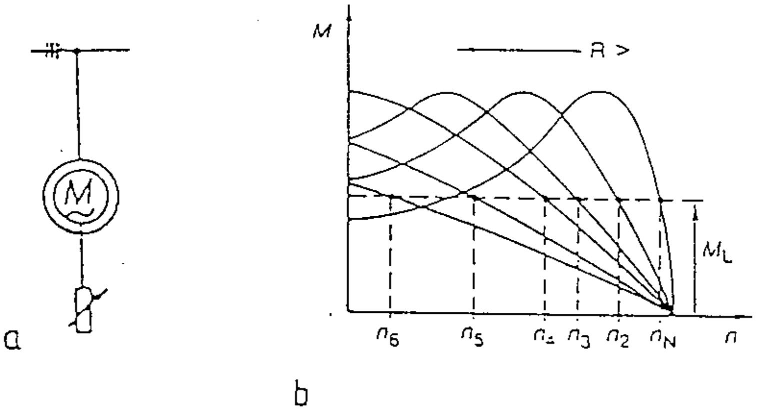


Fig. 20: Three-phase wound rotor motor with regulating resistor in the rotor circuit
a: circuit diagram
b: speed torque diagram

5.2.2 Three-phase wound rotor motor with rotor voltage variation

The speed of the motor is controlled by impressing an external controllable voltage into the rotor circuit. By this means the slip power is fed back into the supply system [4, 13] rather than being dissipated in a resistor, so that losses are substantially reduced.

5.2.2.1 Speed control by booster machine (Scherbius drive)

A booster machine (induction generator (g)) is driven by a three-phase commutator motor(m) which is connected to the sliprings of the main motor (M)(Fig. 21). By varying the excitation of the commutator motor (through an induction regulator) its rotor voltage, which is opposed to the rotor voltage of the main motor, is controlled, thereby controlling the speed of the main motor [14].
The slip power is fed back through the commutator motor and the induction generator into the supply system.
For running up to the lower limit of the speed control range a starter resistor is required.

This type of drive was used until about 1970. Because the brushes and rings require high maintenance, cascades of this type with booster machines are not used today.

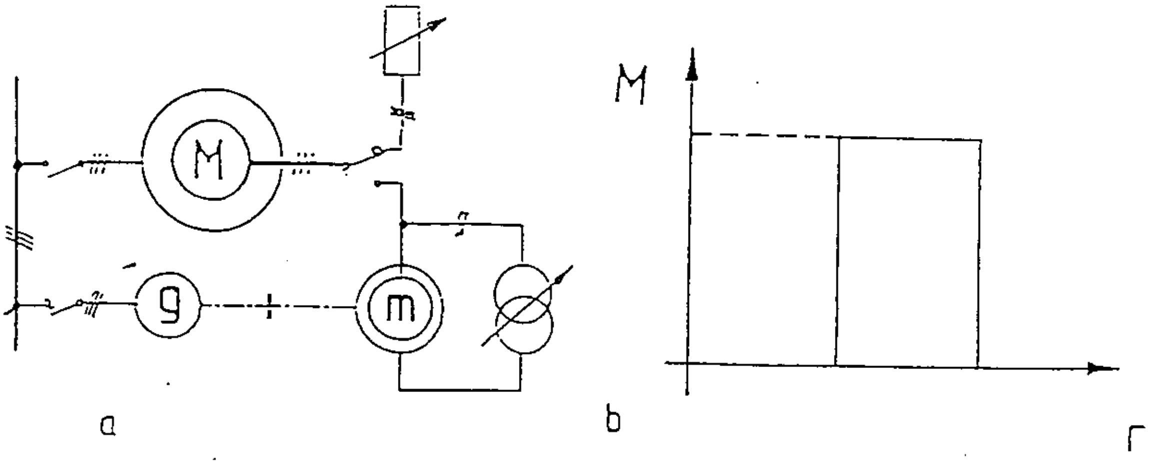


Fig. 21: Three-phase wound rotor motor with booster machine (Scherbius drive)
a: circuit diagram
b: speed torque diagram

5.2.2.2 Speed control by subsynchronous convertor cascade

Because of high maintenance, cascades with booster machines were superseded by subsynchronous convertor cascades following the introduction of semiconductor technology.

By using a static convertor in the rotor circuit of an induction motor, adjustment of speed can be made regardless of the load (Fig. 22). The scheme is referred to as a subsynchronous convertor cascade.

Speed control of the wound rotor motor is achieved by feedback of the slip power of the rotor through a rectifier and a convertor (operating as an inverter) into the supply system.

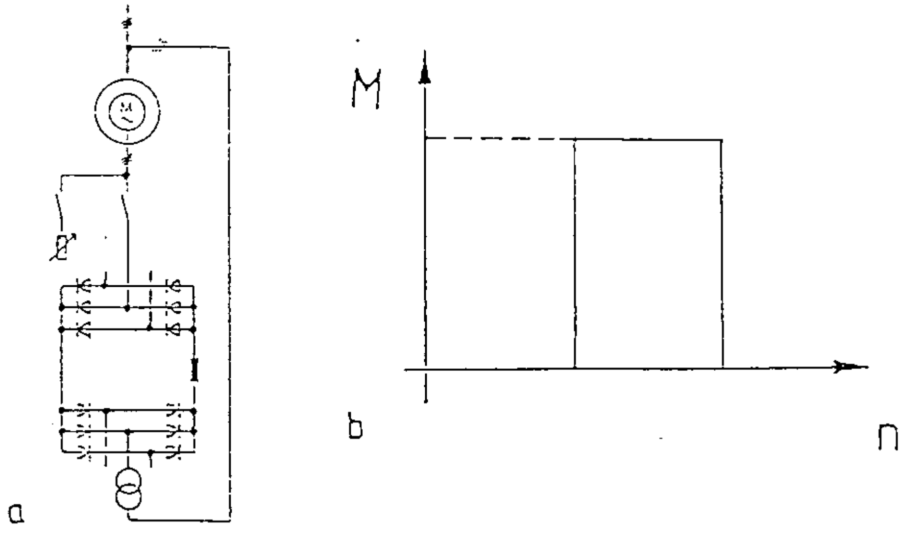


Fig. 22: Subsynchronous convertor cascade
a: circuit diagram
b: speed torque diagram

The rectifier connected to the sliprings of the induction motor is in turn connected to the inverter by a d.c. link. The rotor voltage linearly decreases from the standstill voltage at zero speed to zero at synchronous speed. The speed continuously adjusts itself to the value at which the rectified rotor voltage equals the back-e.m.f. of the inverter. Hence, speed variation is stepless through variation of the delay angle of the line-commutated inverter, the different instantaneous values of rotor voltage and inverter voltage being developed across a reactor in the d.c. link [6, 15, 16].

For economic reasons subsynchronous convertor cascades are not designed for the full speed control range because the slip voltage on the rotor terminals increases with increasing control range and the convertor has to be designed for this voltage. For running up to the lower limit of the speed control range a starter resistor is required.

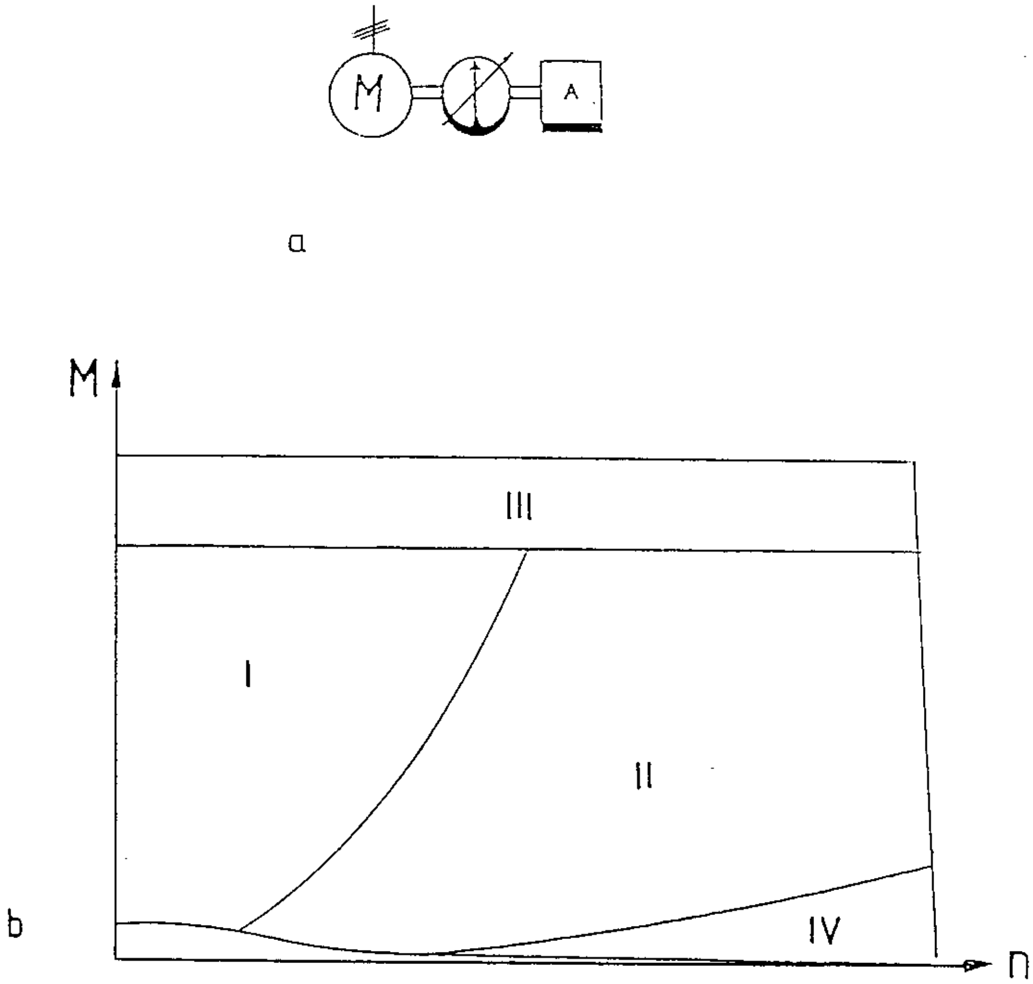
Subsynchronous convertor cascades are predominantly used as low-priced drives for equipment having a square law torque/speed relationship, e.g. boiler feed pumps in power plants, compressors or pumps for water supply and water disposal which require only a limited speed control range. They are suitable for the highest powers (up to about 25 MW) and a normal speed range of 1:3 (in special applications up to 1:20) [9, 10, 17].

By using a direct a.c. convertor the subsynchronous convertor cascade is suitable for multi-quadrant operation, e.g. in traction systems.

The power and control circuits of subsynchronous convertor cascades are simple and the efficiency is high. Conversion of existing wound rotor motor drives is possible. The highest power factor is only achievable at full load and full speed. The brushes and sliprings require occasional maintenance.

5.3 Drives with induction motor and variable speed coupling

A very simple variable speed drive system can be achieved by connecting an induction motor through a variable speed (mechanical) coupling (Fig. 23). Variable speed couplings are of universal use for the stepless speed control of machines in many industrial fields.



Operating ranges: I, IV = starting range
II = regulating range
III = overload range

Fig. 23: Induction motor with variable speed coupling [18]
a: block diagram
b: speed torque diagram

The variable speed coupling transmits the energy input by forcing a fluid mass which is rotated in a closed circuit between an impeller on the driving (primary) shaft and a runner of similar design on the driven (secondary) shaft.

The advantages of variable speed couplings in conjunction with induction motors are robust design, long life, high availability, low maintenance, rapid reaction time and precise speed regulation. The low efficiency at partial load operation is disadvantageous.

Variable speed couplings are available for motor powers up to about 10 MW and speed ranges up to 1:5. The main applications include boiler feed pumps and circulating pumps in conventional and nuclear power plants.

6. Synchronous motor

The speed of a synchronous motor is only adjustable by supplying the stator at variable frequency.

6.1 Speed control with static frequency convertor

For variable frequency operation of synchronous motors two convertor circuit arrangements are used.

6.1.1. Direct a.c. convertor

The direct a.c. convertor consists of 3 reversing convertors, which are controlled in such a way that the synchronous motor receives a three-phase voltage of the desired frequency and phase angle (Fig. 24).

Because the usable frequency range is only 0-50 % of the supply frequency, synchronous motors with direct a.c. convertors are only suitable for low-speed machines, e.g. for hoists and in the cement industry. Multi-quadrant operation is possible.

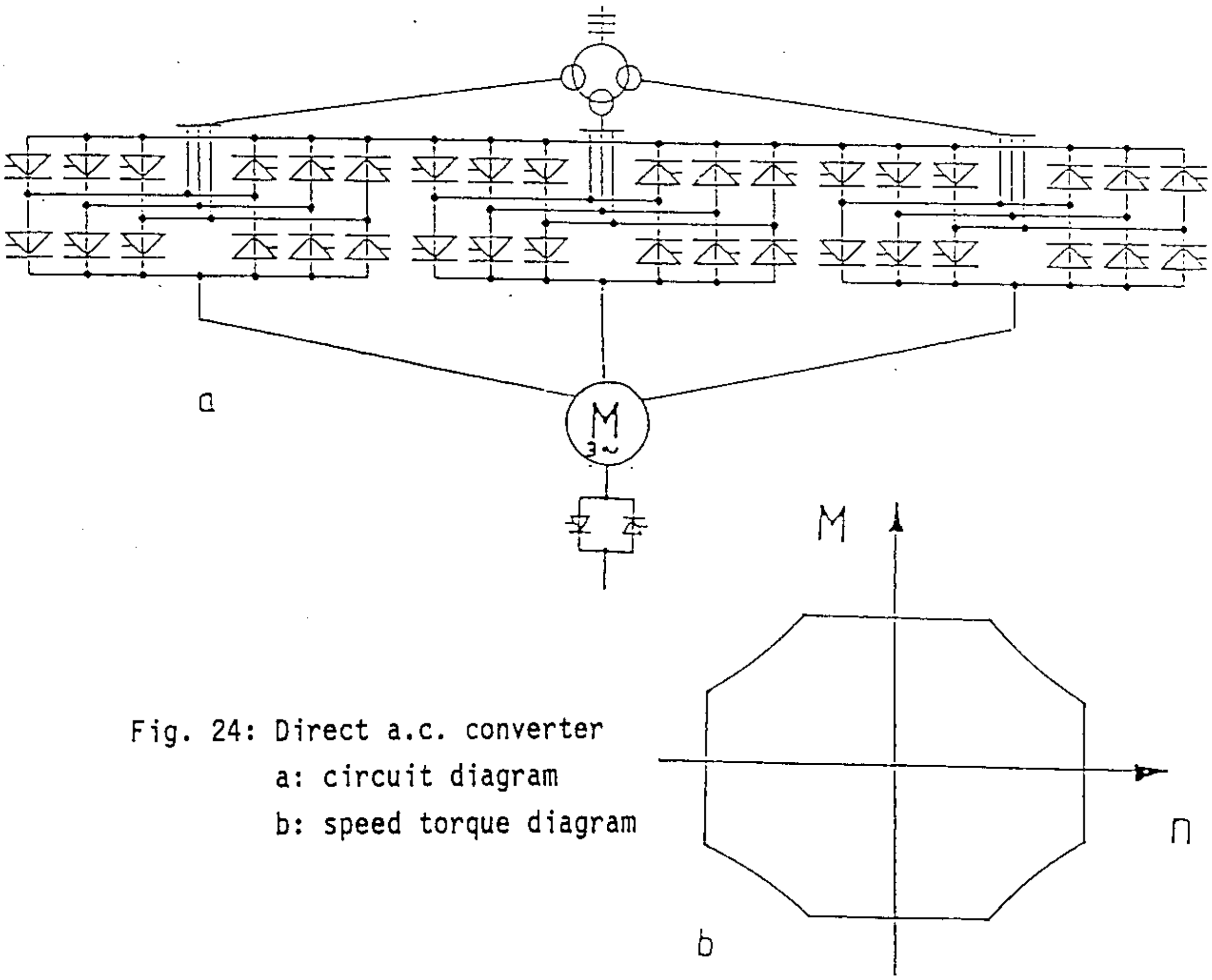


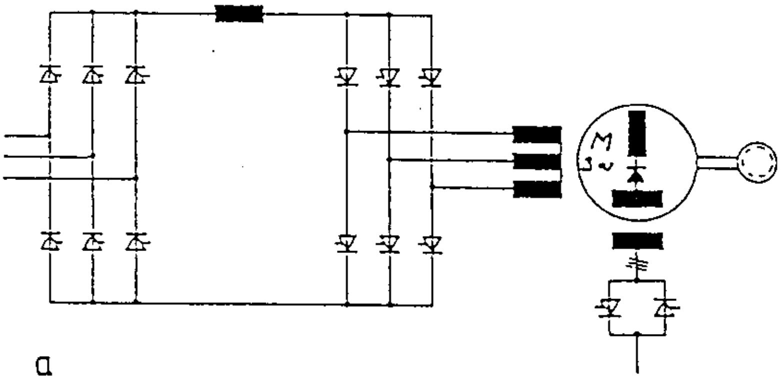
Fig. 24: Direct a.c. converter
a: circuit diagram
b: speed torque diagram

6.1.2 Indirect a.c. convertor

6.1.2.1 Current source d.c. link convertor (convertor-fed motor, brushless motor)

This indirect a.c. convertor consists of two identical static convertors and a d.c. link with d.c. smoothing reactor (Fig. 25).

To control the motor, the line-commutated convertor operates as a rectifier and adjusts the speed. It is connected via the d.c. link containing a smoothing reactor for energy storage to the motor convertor, which operates as a load-commutated inverter (load commutated inverter drive or LCI drive).



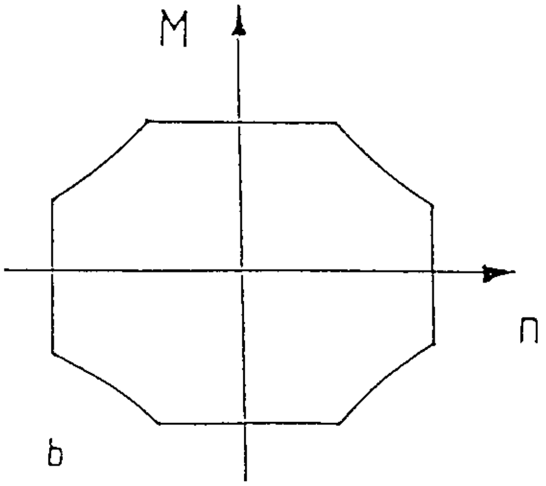


Fig. 25: Convertor-fed motor
a: circuit diagram
b: speed torque diagram

The control system can be modified to provide multi-quadrant operation without changing the power circuit of the convertor.

The synchronous machine can only provide the inverter commutation voltage for switching of the stator current above a certain minimum speed. For this reason the motor inverter may need to be controlled by a rotor position transmitter coupled to the motor shaft (or by other means) for startup of the motor. Above about 10 to 15 % speed the motor voltage is high enough for load-commutated operation [19, 20].

The synchronous machine has brushless excitation consisting of rotating diodes, an asynchronous exciter which operates as reverse field machine, and a three-phase a.c. controller for adjusting the exciting current.

The motor voltage and speed are normally proportional (constant torque). In field-weakening operation however a constant motor voltage and rising speed can be achieved (torque reduction).

In principle the operation and dynamic response of a convertor-fed synchronous motor correspond to a separately excited convertor-fed d.c. motor. In the convertor-fed synchronous motor system however the mechanical d.c. motor commutator, which is subject to wear, has been replaced by an electronic commutator. Robustness, high level of efficiency even under partial load conditions and at intermediate speeds, and low maintenance of the brushless synchronous motor have been combined to provide the optimum control equivalent to the convertor-fed d.c. motor.

The convertor-fed synchronous motor is available up to about 50 MW and a maximum speed of 7000 r.p.m., without using a gearbox. Above 2 MW 12-pulse circuits are preferred to 6-pulse because they impose lower levels of harmonics on the supply system and smoother torque on the drive shaft. Convertor-fed synchronous motor applications include large boiler feed pumps in coal-fired power plants, cooling water circulating pumps in nuclear power plants and gas turbine and hydro-generator starters (generator working as motor) [8, 21].

6.2 Drives with synchronous motor and variable speed coupling

A drive with synchronous motor and variable speed coupling is more complicated and more expensive than an induction motor with a variable speed coupling. For running up to synchronous speed from rest the synchronous motor requires a separate starting motor or a squirrel-cage winding in the pole spider. Otherwise the same advantages and disadvantages are applicable.

7. Selection considerations for various applications

To select a large variable speed drive for a special application several solutions are available based on three types of electrical machine and several variants of speed control. To find the best solution technical and economic criteria have to be specified and determined [4].

In the case of large drives low-loss speed control is usually desirable and even essential. Because only convertor-fed drives achieve this, the following drive variants are the ones which should be considered:

a) convertor-fed d.c. motor (DCM) (chapter 4.3.2)
b) convertor-fed three-phase squirrel-cage motor (SCM)
  - direct inverter drive (DI-SCM) (chapter 5.1.3.1)
  - current source inverter drive (CSI) (chapter 5.1.3.2.2)
  - voltage source inverter drive (VSI) (chapter 5.1.3.2.1)
c) convertor-fed synchronous motor (SM)
  - direct inverter drive (DI-SM) (chapter 6.1.1)
  - load commutated inverter drive (LCI) (chapter 6.1.2)
d) subsynchronous convertor cascade (SCC) (chapter 5.2.2.2)

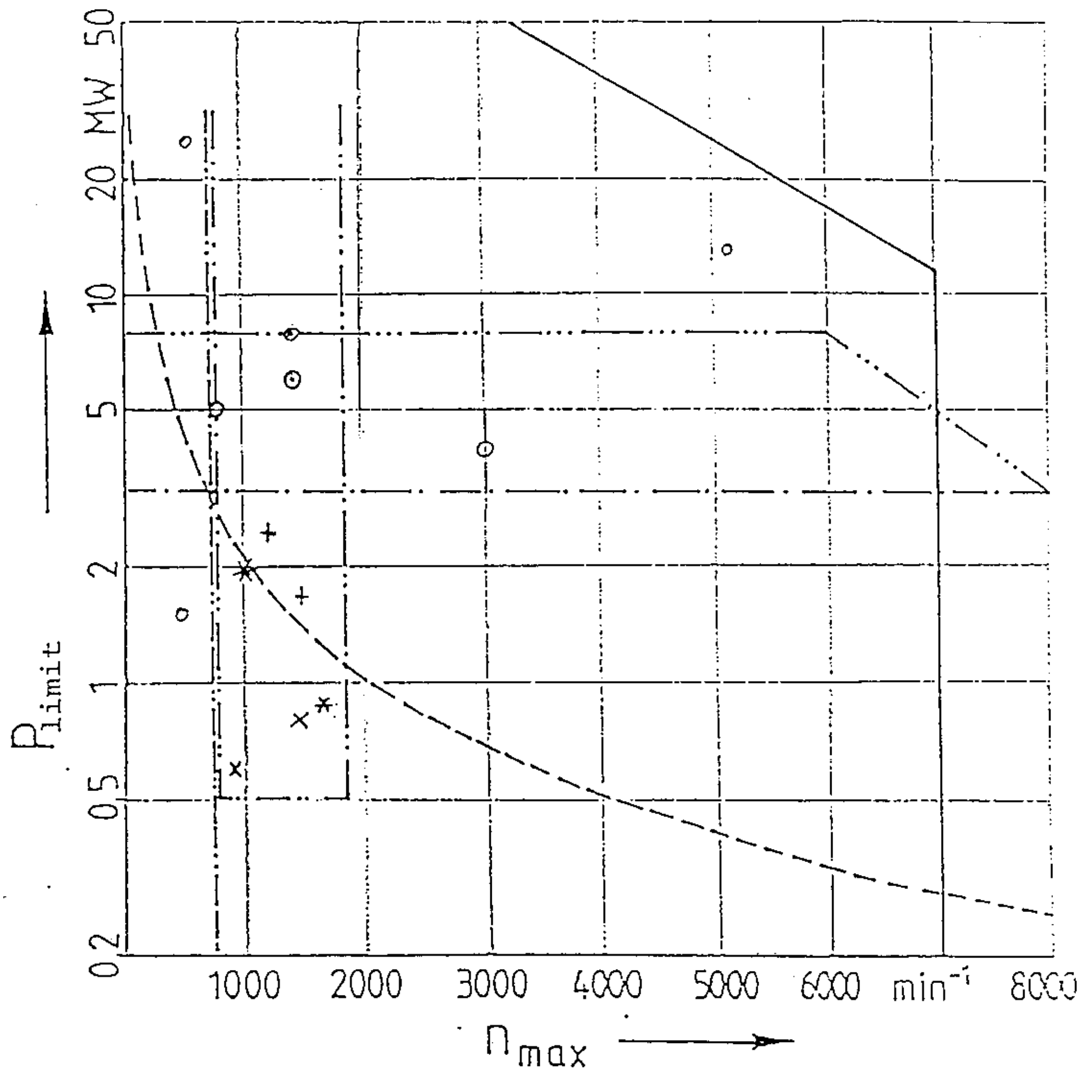
If a low-loss speed control is less important, variable speed couplings can be considered (chapter 5.3, 6.2).

The following factors are suggested as relevant for consideration:

7.1 Power and speed range
7.2 Speed control range
7.3 Dynamic response
7.4 Effiency
7.5 Power system considerations with respect to harmonics and other possible effects
7.6 Reliability
7.7 Investment costs and operating expenses

7.1 Power and speed range

Fig. 26 shows the limits with regard to power and speed, which are usual today as derived from the literature [4, 11]. These limits take into consideration technical



drive	limit	(∗)	drive	limit	(∗)
DCM	- - - -	×	DI-SCM/SM	— — ··	□
CSI	—·—·	∗	LCI	———	○
VSI	—···—	+	SCC	—··—	⊙

Fig. 26: Power and speed ranges of convertor-fed drives

limits and economic factors. The results of the questionnaire have been added to Fig. 26 (*) and show a good correlation with the literature.

7.2 Speed control range

Today the following typical speed control ranges are usual:

drive variant	typical speed control range
convertor-fed d.c. motor (DCM)	1 : 100
direct a.c. convertor with induction motor or synchronous motor (DI-SCM, DI-SM)	1 : 200
pulse convertor (VSI, chapter 5.1.3.2.1.2)	1 : 200
current source d.c. link convertor (CSI)	1 : 20
convertor-fed synchronous motor (LCI)	1 : 20
subsynchronous convertor cascade (SCC)	1 : 3

7.3 Dynamic response

The dynamic response of a drive system is mainly related to variability of torque and speed and characterised by the accuracy of the adjustment of these values, i.e. how fast and precisely the drive is able to respond to load variations. The dynamic response of speed controlled drives is influenced by the proportion of rotor diameter to rotor length (rotor slenderness) and is otherwise determined by the control system elements.

The dynamic response of a.c. drives is basically comparable with those of d.c. drives with reversible convertors. In the case of d.c. motors the dynamic response is limited by the minimum required armature diameter and consequent larger moment of inertia. Hence, a.c. drives have advantages in terms of speed controllability in some ranges of application since these drives usually have much smaller moments of inertia.

In comparison with the pulse convertor the current source a.c. convertor has a higher torque control response time owing to the smoothing reactance in the d.c. link.

7.4 Efficiency

Fig. 27 shows the efficiency range of the 3 electrical machine types (without convertors) as a function of rated power at rated speed [4].

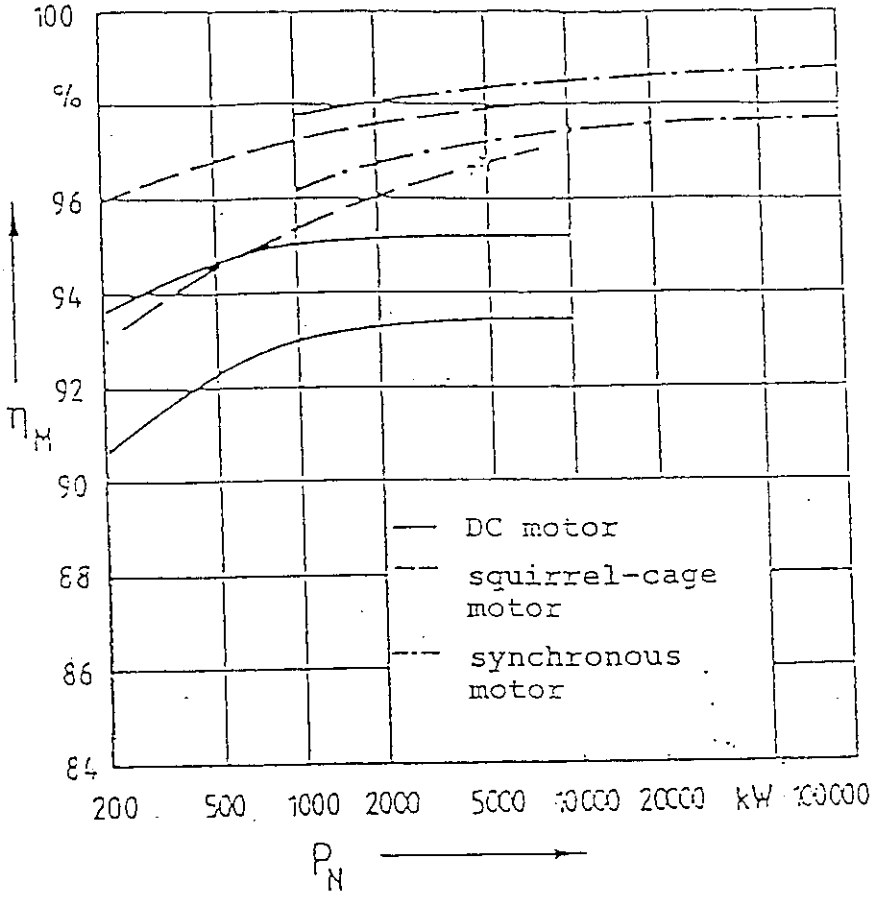


Fig. 27: Efficiency ranges of electrical machines (without convertors)

The efficiency of a squirrel-cage motor is about 2 - 3 % higher than that of a d.c. motor. Synchronous motors have an efficiency about 0,2 - 0,5 % higher than squirrel-cage motors.

Generally the efficiency of convertors is slightly higher than the efficiency of machines. However the wave-form effects of convertors bring about some reduction in electrical machine efficiency.

Fig. 28 shows the efficiency ranges as a function of rated power at rated speed for the 3 types of electrical machine when fed from a convertor [4]. For comparison of efficiencies it is necessary to account for the part-load range, which would be difficult to illustrate and has not been included in this report. Information from manufacturers should be compared.

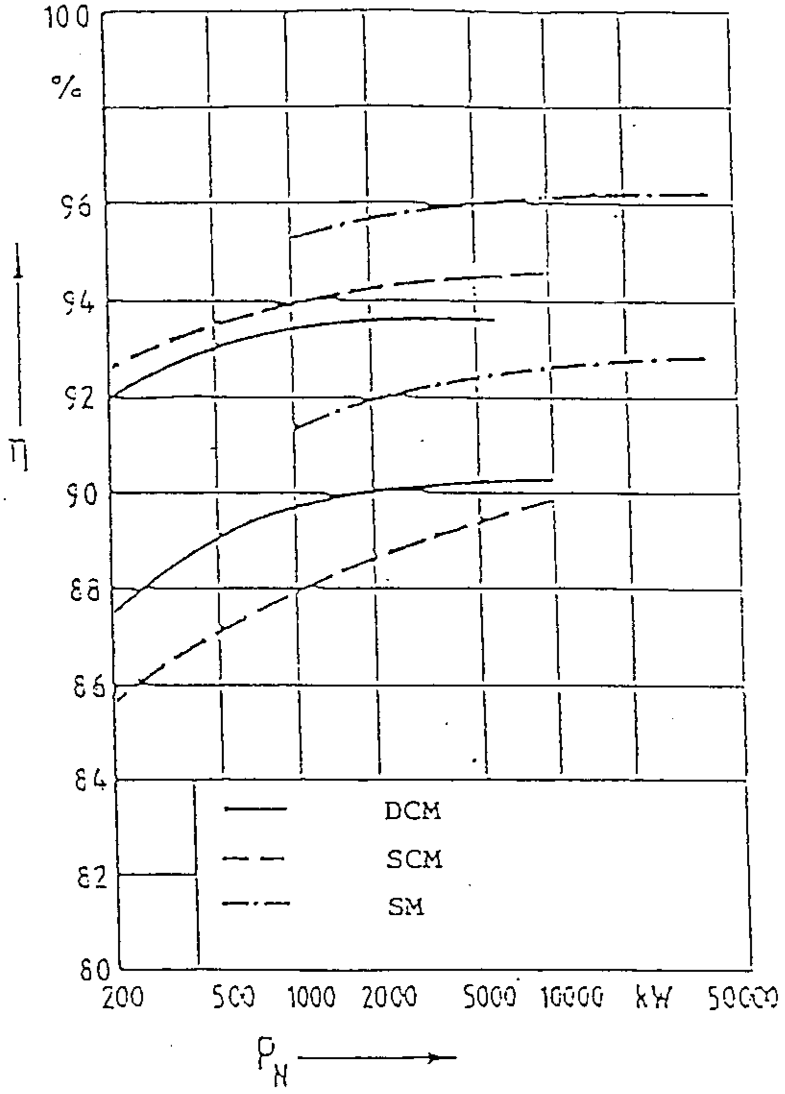


Fig. 28: Efficiency ranges of convertor-fed machines (including the convertor).

7.5 Power system considerations with respect to harmonics and other possible effects

Convertors including those used on variable speed drives affect the power system and other equipment in the supply system. Indeed the operation of convertors leads to disturbances to the supply system. Convertor-fed drives have reactive power requirements and produce current harmonics [22, 23].

a) Reactive power (fundamental frequency reactive power)

Line-commutated convertors impose a lagging reactive power load on the a.c. link, a distinction being made between control reactive power and commutation reactive power:

- control reactive power
  The control reactive power is caused by the phase angle control of the convertor. With increasing delay angle the control reactive power increases.

- commutation reactive power
  The commutation reactive power is caused by the current changeover from the outgoing thyristor to the oncoming thyristor and attains its maximum at zero delay angle setting.

A comparison of the different variable speed drives with regard to the reactive power requirements shows the following:

type of convertor drive	requirement of reactive power (control reactive power)
current source a.c. convertor	high
voltage source a.c. convertor (pulse convertor)	low
convertor-fed d.c. motor	high
subsynchronous convertor cascade	very high

b) Current harmonics

The switching of convertor thyristors produces rapid current changes, which cause a distortion of the sinusoidal current. In the case of convertors which receive commutation power from the supply system, the line voltage is distorted. The line current contains harmonics of order 5,7,11,13,17,19......
In case of convertors with rectifiers and inverters interharmonics of order 6,12,18....occur.

A comparison of the different variable speed drives with regard to current harmonics demonstrates the advantage of voltage source a.c. convertors (pulse convertors).

Generally supply disturbance from the drive is determined by the following parameters and equipment:
- short-circuit power of the supply system
- reactances between supply system and convertor (e.g. transformers)
- supply-side and load-side convertor circuits
- type and mode of operation of the drive

Arrangements for reducing the power system effects

a) Reactive power

1. Circuit arrangements

   Application of half-controllable convertor connections

   Application of sequential phase control where two or more (partial) convertors are used (seldom applied for reasons of the increased current harmonics and higher equipment costs)

   Application of pulse-width modulation, where line convertors are used.

2. Compensation arrangements

   Application of static reactive power compensation arrangements rated according to the reactive power level.

   Application of dynamic reactive power compensation arrangements (reactive power convertor) (seldom applied because of high equipment costs)

b) Current harmonics

1. Circuit arrangements

   Application of convertors with pulse numbers higher than six, e.g. 12 pulse convertors

   Application of two 6 pulse convertors with a three-winding transformer (Fig. 29) or two two-winding transformers(Fig. 30), whose secondary voltage vector groupings are offset with respect to each other by 30°.

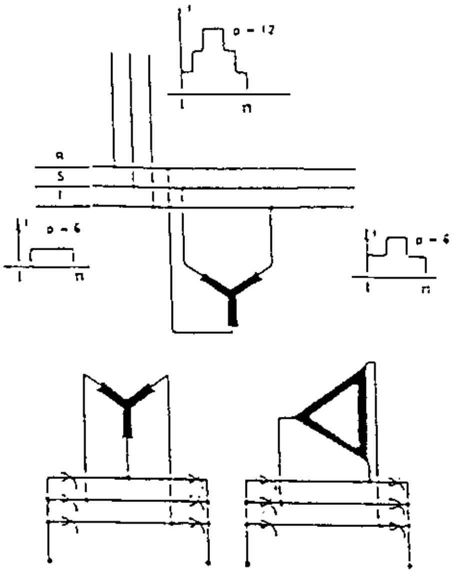


Fig. 29: Two 6-pulse convertors with a three-winding transformers [24]

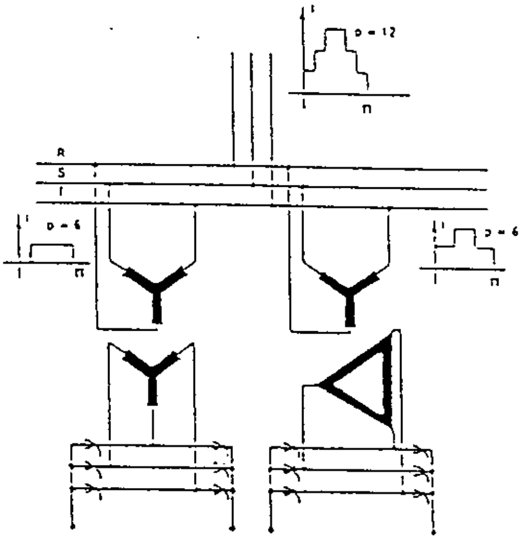


Fig. 30: Two 6 pulse convertors with 2 two-winding transformer

Application of phase displacement in an installation of several convertors in a plant system

Application of pulse-width modulation for convertor control

Application of electrical separation criteria between circuits supplying power to variable speed drives and circuits supplying power to very sensitive equipment, e.g. compensated lighting circuits, computers and microprocessors. This is especially relevant when diesel generators are used for supplying power to various loads including both variable speed drives and sensitive equipment because of the relatively low short circuit power level.

Some national standards and recommendations in relation to current harmonics are listed in Appendix 3.

2. Compensation arrangements

Application of static harmonic absorbers
(filter circuits)

The convertor pulse number and the supply short curcuit power are the main influences on the levels of current harmonics. For drives in the megawatt range 12-pulse convertors are usually required. At high levels of short circuit power, typical in power plants, no additional arrangements are required for reducing current harmonics. This was confirmed by answers to the questionnaire.

If pulse convertors are used overvoltage problems must be considered (chapter 5.1.3.2.1.2, p. 23).

7.6 Reliability

Generally the reliability of convertor-fed electric motors is significantly higher than drives using steam turbines or variable speed couplings because they minimize the number of wearing parts and highly stressed mechanical and electrical components. In permanent service convertor-fed drives are practically as reliable as the supply system in a power plant. Additionally, during the starting phase, negligible shock loads are imposed on the electrical and mechanical components.

Induction and synchronous motors have no commutator and therefore a higher reliability than d.c. motors. In the case of highly stressed large d.c. drives the commutator is a primary weakness, and in the case of wound rotor induction motors reliability is limited by the sliprings. By applying convertor-fed squirrel-cage induction motors and synchronous motors the highest reliability is realized.

The reliability of electronic components is higher than mechanical components. Electronic components are tested and are permanently monitored in service. In the power part of convertors thyristors or GTOs are applied with redundancy (n+1connection). In the literature the MTBF (mean time between failures) of convertor-fed drives is given as over 3 years and the MTTR (mean time to repair) as about 0,5 hours [25].

In some special cases however the application of a bypass-switch for convertors can be considered for maintenance purposes. This will be practical, if the short circuit level of the power supply is sufficient for operation of the induction motor without convertor.

7.7 Investment costs and operating expenses

The investment costs are dependent on market conditions and are changing with progress in engineering technology. Investment for convertor-fed variable speed drives and associated equipment is typically lower than for comparable turbine drives. Convertor-fed variable speed drives amount to a virtually total and self-contained power and control package for the service concerned [22]. Because it is very difficult to obtain comparable costs from manufacturers and users for the many different variants of variable speed drives, Fig. 29 shows only a relativity of costs for common applications [4].

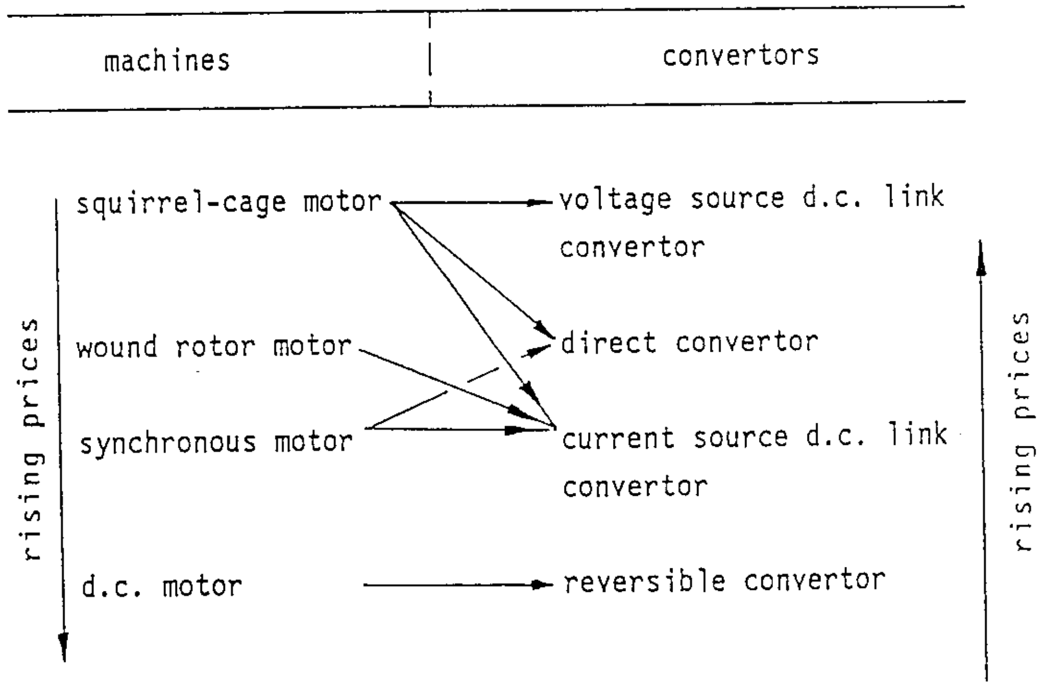


Fig. 29: Relativity of investment costs for usual circuits of electrical machines and convertors

Operating expenses are dependent on energy and maintenance costs. Energy costs are frequently well below the comparable costs for gas or steam because of the far higher efficiency of electrical machines.

In applications of convertor-fed squirrel-cage motors and brushless synchronous motors, operating expenses are sharply reduced through the elimination of wearing parts and little or no requirement for scheduled maintenance. Only electrical machines with sliprings or commutators need significant, regular scheduled maintenance. Dependent on the power rating, costs for the consumption of cooling water and lubricants may be considered.
No specialist knowledge of electronics or programming is necessary to operate and routinely maintain the electronic equipment.

The application of convertor-fed drives has the advantage of low starting current and therefore a low contribution to the short circuit level. This can lead to lower switchgear costs.
A further reduction of investment costs can be reached, if spare drives are equipped with simpler devices.

8. Conclusion

This report surveys all practicable types of large variable speed electrical machines (> 200 kW) and their control systems as applied in the past and as used today. The possible circuits are described and the speed torque diagrams are shown. Criteria, advantages and disadvantages are listed to facilitate the choice of suitable variable speed drives.

Convertor fed drives should be considered paramount for application in power plants because of their low loss advantage.

Limits in power and speed ranges using present engineering technology have been documented. The further development of modern semiconductor techniques should promote further increases in power and speed ranges.

The questionnaire responses indicated that the application of convertor-fed variable speed drives in power plants is not wide spread. The reason for this is that the investment costs of variable speed drives are relatively high, and particularly uneconomic in base-load power stations.
On the other hand, if the power station is subject to regular load variations variable speed drive can be economically justified. The same can be the case if the motor has to be oversized because of uncertain mechanical design where fluid or gas flow is being regulated by mechanical means rather than by variable drive speed.

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CIGRE Study Committee 23
Working Group 08

Country: ....
Utility: ....

Questionnaire

on the application of adjustable speed drives > 500 kW in power stations

Generator capacity: ....MW

Equipment data →	Equipment 1) reported on		Rating data				Type of motor				Type of drive					Other drivers 2)				No. of 3) Quadrants	6 or 12 pulse	Process 4) variable	No. of forced shutdowns 5)	Operating hours to-date	Estimated 6) equipment cost
↓ Application	Actually in use ↓since	Planned↓	power (kW)	speed (rpm)	min-speed-max (from - rpm - to 7))	Line volt 8)	SCI	SM	WRM	DC	LCI	CSI	VSI	SCC	PF correction yes no 9)	FS	ST	HVC	Others 10)						
boiler feed pump																									
reactor feed pump																									
cooling water pump																									
heating water circulation pump																									
condensate extraction pump																									
induced draft fan drive																									
forced draft fan drive																									
coal mill drive																									
heating oil separator drive																									
conveyor belt drive																									
gas turbo generator starting converter 11)																									
pumped storage generator (starting) converter 12)																									
others (specify):																									

Use separate sheets for any additional information you may have to offer!

Legend to abbreviations:

SCI	Squirrel cage induction motor
SM	Synchronous motor
WRM	wound rotor induction motor
LCI	Load commutated inverter drive
CSI	Current source inverter drive
VSI	Voltage source inverter drive
SCC	Subsynchronous converter cascade
PF	power factor correction and/or harmonic filtering equipment
FS	Fixed speed electric motor, mark synchronous (S) or induction (I)
ST	Steam turbine
HVC	Hydro viscous clutch with fixed speed induction motor

Remarks:

1). Please list both, your actual equipment in use now and your future (next 5 years) planned equipment for each application indicated. If you have more than one drive of the same rating in use or planned, please indicate their quantity here. If the sizes are different use a separate line or sheet for each one.

2). "Other" drives are not actually part of this survey but are listed here because they are typical alternatives to electric motor adjustable speed drives for the applications listed here.

3). This is another term for "direction of driving" and "driving/braking". 1 = driving in one direction only, 2 = driving & braking in one direction, 4 = driving & braking in both directions

4). This is the actual fluid, gas or solid medium whose flow, pressure or quantity is controlled by the variable speed drive

5). To compare reliability data of the various systems, this figure should reflect your best knowledge or estimate of the *number of unscheduled shutdowns per annum* of the particular system

6). To enable relative comparisons between the available alternatives, you should list the approximate ***net capital investment cost*** for the particular drive system at time of purchase (year indicated in first column)

7). The desired minimum speed is the *lowest continuous operating speed.* The maximum speed is the *highest operating speed* of the set, not the overspeed test speed.

8). List the distribution voltage level the drive or its converter transformer is connected to

9). Check here if either power factor correction capacitors or harmonic filter circuits are installed in your system *for the drive listed.* The p.f. as a function of the kind of drive and of the speed control range, and the magnitude of current harmonics caused by the drive can be estimated from the other data given here. Important: If you have experienced EMC problems (electromagnetic compatibility) in connection with the installation of electric motor variable speed drives, please list those experiences and the measures to combat them on a separate sheet. This is a prime concern of the study committee

10). List any drive system here that is not specifically mentioned in the questionnaire and give details on a separate sheet, if possible

11). List both the rating and speed of the generator and the rating of the starting converter

12). If the application is purely the *starting* of the pump motor, list both the rating and speed of the pump motor and the rating of the starting converter. If the application is a variable speed hydro generator with frequency converter, list rating and speed of hydro generator.

Appendix 2: Results of the questionnaire

Application	Number of units			Type of motor				Type of drive				
	nuclear	thermal	hydraulic	SCI	SM	WRM	DC	LCI	CSI	VSI	SCC	HVC
boiler feed pump		73		33	2	38			2		3	33
reactor feed pump	1				1			1				
cooling water pump		2		1		1		1			1	
heating water circulation pump		2					2					
condensate extraction pump		5		2		2	1		1	1	2	
induced draft fan drive		8		8								8
forced draft fan drive		19		16	3			3	8			8
coal mill drive		2										
heating oil separator drive												
gas turbo generator starting convertor		24						24				
pumped storage generator (starting) convertor			56		54	2		54			2	
cooling tower fan		3		3								3
reactor circulation pump	2				2			2				
reactor recirculation pump	1				1			1				
gas injection fan		6			6					6		
sodium secondary pump	1				1			1				

Legend to abbreviations: see questionnaire (Appendix 1)

Appendix 3: Standards and recommendations about current harmonics

1.) Australian Standard AS 2279.2-1991
Disturbances in mains supply networks
Part 2: Limitation of harmonics caused by industrial equipment

2.) Enineering Recommendations G5/3
Limits for Harmonics in the U.K. Electricity Supply System

3.) ANSI/IEEE Std 519-1981
IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters.

4.) VDE Specification 0160
Specification of Electrical Equipment for Electrical Power Installations with Electronic Devices

5.) Grundsätze für die Beurteilung von Netzrückwirkungen
2. überarbeitete Ausgabe 1987
Vereinigung Deutscher Elektrizitätswerke - VDEW - e.V. Frankfurt am Main

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