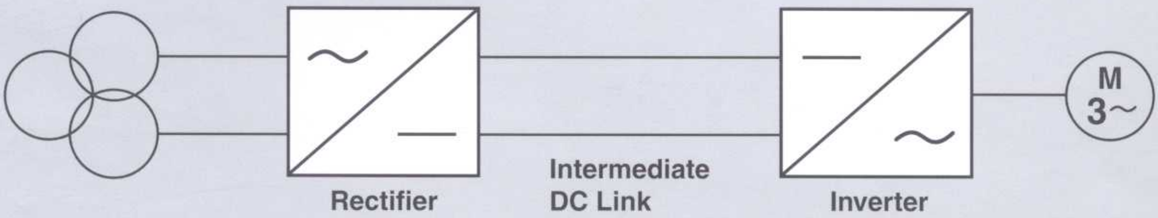
A Guide to Standard Medium Voltage Variable Speed Drives

Part 2:

Choosing a motor control platform and drive system



A guide to medium-voltage standard AC drives

Who should read this guide

This Technical Guide is available in six parts from the ABB address given on the back cover.

It is aimed at the key decision makers engaged in the specification, selection, purchasing, installation and/or commissioning of medium-voltage AC variable speed drives, as a standard solution.

It is therefore aimed at electrical, mechanical and plant engineers as well as managers, consultants and technicians.

There is a new thinking within industry. Standard, 'off-the-shelf' medium-voltage AC drives can often be a more cost effective solution than traditional 'engineered' drive systems, which are tailor made and consequently more costly.

This Technical Guide series, therefore, aims to give a basic understanding of the technologies and practices presently available to those considering purchasing 'standard' medium-voltage AC drives.

However, in a Technical Guide of this nature it is not possible to give an in-depth analysis of all aspects of selecting, purchasing, installing and commissioning medium-voltage AC drives. The reader is advised to consult ABB for more detailed information.

Contents

Introduction

What is a variable speed drive ?

A power electronic device that controls the speed and torque of an electric motor is often called a Variable Speed Drive (VSD)*. It takes energy from the mains and controls the energy flow to the motor creating different motor speeds and torques as required.

In this way, the drive can control the variables of a process, such as flow, by controlling the speed of a pump.

When controlling torque, the load determines motor speed; when controlling speed, the load determines motor torque.

Initially, DC drives and motors were used because speed and torque could be controlled without the need for sophisticated electronics. However, high maintenance requirements of DC motors have led to a decrease in their popularity.

AC drives and motors are the most common in industry as AC motors are inexpensive and need little maintenance. AC drives have been developed to the extent where their torque and speed control performance is as good as DC systems.

* Footnote: Beware of the conflicting jargon that is often used to describe a Variable Speed Drive. A Variable Speed Drive is often referred to as a VSD, an AC drive, a converter, an inverter or quite simply a drive. Other alternatives include VVVF = Variable Voltage Variable Frequency; VFD = Variable Frequency Drive; and ASD = Adjustable Speed Drive

What to consider when selecting a medium-voltage AC drive

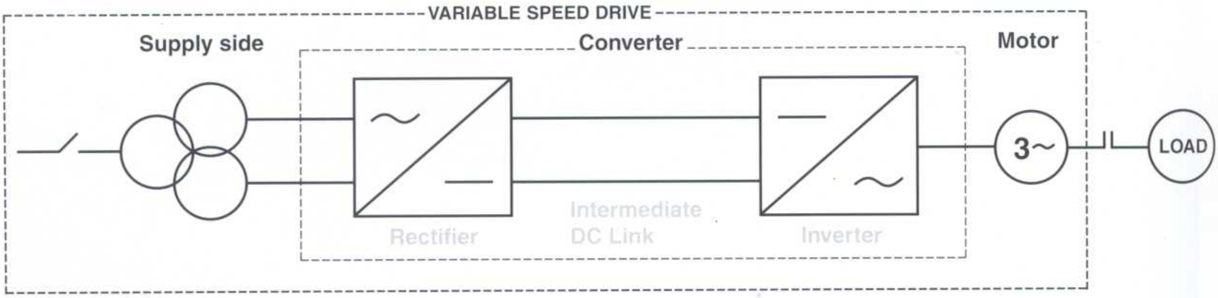
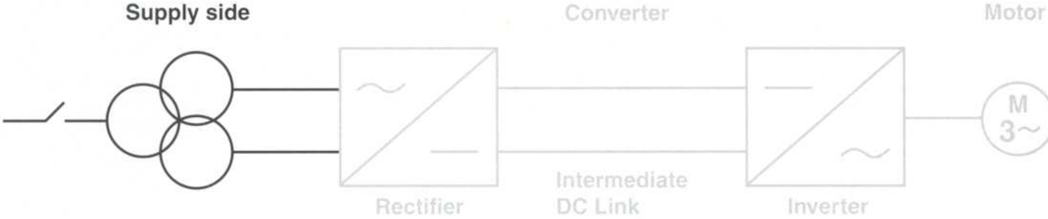


Figure 1: A simple representation of a drive system

When choosing a medium-voltage AC drive, considerations need to be given to each element shown in the above schematic:

- **The supply side**
- **The medium-voltage AC drive** (alternatively called '**converter**')
- **The motor**



Harmonics: The main concern on the input side is the presence of harmonics and the need to ensure that the AC drive conforms to harmonic regulations such as IEEE 519.1992 and the UK's G5/3. Furthermore, the drive should comply with these local harmonic regulations without the need for additional harmonic filters.

Harmonics that are the highest in amplitude, and therefore, normally the most problematic in medium-voltage systems, are the 5th and 7th harmonics. These can be removed by using, for example, a 12-pulse uncontrolled diode bridge rectifier. A 24-pulse unit can be used for weaker networks or where more stringent harmonic requirements apply.

Input Power Factor: Ideally, the higher the power factor the greater the cost savings will be as no extra reactive power compensation equipment is needed and cables and transformers can be dimensioned for lower current. This also avoids penalties from utilities.

A fundamental power factor better than 0.97 and a total power factor better than 0.95 should be the goal. Additionally, the power factor should be constant over the entire speed range without the need for additional power factor correction equipment because the goal is to run the drive at other than full speed and so power factor needs to be constant. With some drive topologies, this is not possible (see page 7).

Input isolation transformer: It should be possible to position the transformer both inside the electrical room, or, if conditions dictate, outside the electrical room.

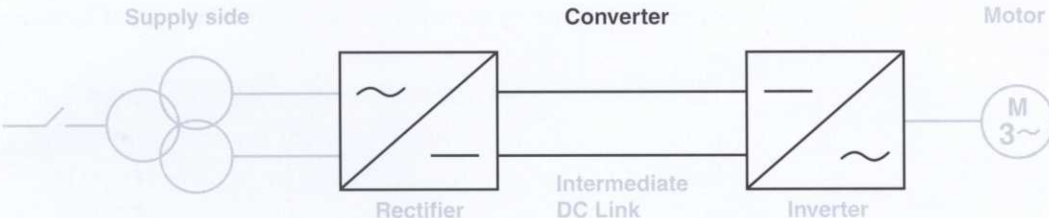
However, the ability to locate a transformer anywhere other than the electrical room, depends on the choice of drive system or topology (see page 7). For example, a three-level Voltage Source Inverter topology, substantially reduces the number of cables between the input isolation transformer and the converter.

Other types of multi-level topology can need anything from

27 to 45 cables, making it problematic to place the transformer away from the converter.

The freedom to choose the transformer location brings cost savings, firstly from a smaller drive size, as the large transformer does not need to be sited in the electrical room. Secondly, the losses from the transformer are not being dissipated into the room. Therefore, the cooling requirements for the electrical room can be greatly reduced. This is especially important in locations that have a high ambient temperature.

Converter



There are many considerations to be taken before purchasing a medium-voltage AC drive, but the principal requirements from any drive should be:

• **Small overall dimensions** - This is especially important in industries such as offshore and the oil and gas sector, where the cost of real estate is high. Today, medium-voltage AC drives can measure as small as 3 - 4.5 metres long, only 900mm deep and 2 metres high.

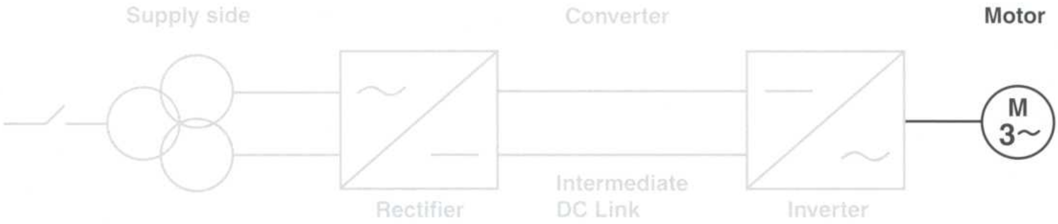
Small size has been mainly achieved by new technological developments, particularly in the field of power semiconductor switching devices.

See Part 3 of this Technical Guide series to discover the secrets to small size.

• **Low audible noise** - Health and Safety legislation in many countries is demanding noise levels that do not subject personnel to harmful or irritating noise.

• **Fully compliant to the necessary EMC regulations** - While drives must not pollute the environment with high levels of electro magnetic radiation, of equal importance is the need to ensure that the installed drive is immune from the effects of radiation being emanated from other equipment.

• **Higher efficiency** - is important if energy costs are to be reduced.



Careful consideration should be given to the following:

- **Compatibility** with standard squirrel cage induction motors. There are three main concerns:

1. **Derating:** Because harmonics cause additional heating in a motor, this leads to the need to derate the motor. When purchasing a motor for use on a medium-voltage drive, enquire, from the drive supplier, as to whether derating is necessary.

2. **Voltage stress:** This can damage motor insulation. Drives which incorporate fast switching power semiconductors can have a high voltage rate of change and it is this which can damage the motor. An output filter which gives a sine wave output can overcome this problem.

3. **Common mode voltages.** These are high frequency voltages that can also damage motor insulation. To be able to retrofit a drive onto an existing motor, it is essential that the converter does not subject the motor to high common mode voltages.

   Common mode voltages can be overcome, depending on the drive system (topology) selected (see page 7). For example, a three-level Voltage Source Inverter with an output filter arrangement, can avoid common mode voltages by earthing the star point of the output filter. This simple solution eliminates the dangerous voltages and provides one less concern when carrying out a retrofit installation.

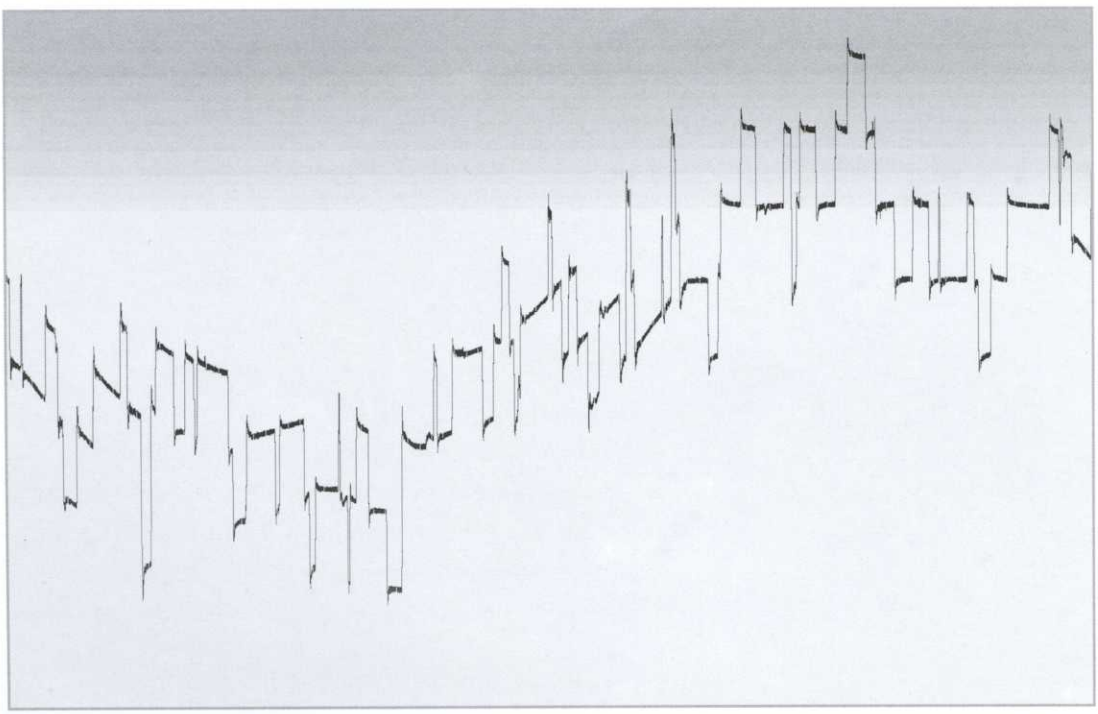
• **Voltage reflections:** This is a specific concern at medium-voltages, especially when retrofitting a drive onto an existing motor as the condition or the quality of the insulation of that motor may not be known. If left unchecked voltage reflections can seriously damage motor insulation.

• **Torque pulsations:** If a drive produces high torque pulsations this can excite mechanical resonances and can damage the motor shaft, the gear box (when used) and the load.

• **Motor noise:** Some converters, when retrofitted on motors, produce extra motor noise. The motor runs louder and this extra noise should not be tolerated.

• **Torque and speed performance:** The demand, today, is for the same level of torque and speed performance in medium-voltage drives that is possible with some of today's low-voltage drive equipment. The solution rests with the choice of motor control platform (see page 14).

Typical common mode voltages are a series of voltage spikes superimposed on an AC waveform



The solution

The solution to all the above considerations for **supply, converter** and **motor** lies in the choice of converter (also referred to as medium-voltage AC drive).

It is important, therefore, to have an understanding of the basic blocks which make up a medium-voltage AC drive, namely the type of **motor control platform** and the **topology** on which the drive is based.

The topology: is the name given to the various types of electrical configuration for AC drive systems, employing synchronous and induction motors of all types for a variety of applications.

The motor control platform: lies at the heart of the drive system. It is to be found within the converter element of the AC drive topology. It is the motor control platform that controls the flow of energy to the motor, which ultimately delivers the desired torque and speed accuracy.

Drive System Topologies

Introduction

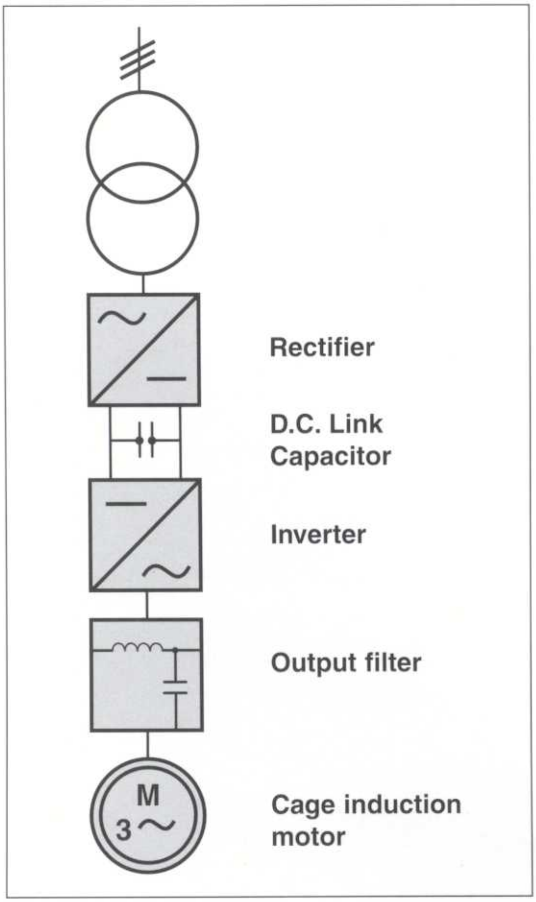
This section looks at the various arrangements - often referred to as topologies - for medium-voltage AC drive systems.

It looks at the configuration, applications, performance and speed/ power limits of each type commonly in use by industry today.

Voltage-Source Inverter (VSI)

The system consists of a Voltage Source Inverter with a constant DC voltage in the DC link. A 12 or 24 pulse rectifier is used on the supply side, to ensure harmonics to the network are kept to a minimum. The capacitor in the DC link smoothes the DC voltage and supplies reactive power to the motor. The self-commutated inverter unit uses Gate Turn-Off thyristors, High Voltage IGBTs or IGCTs, with both two or three level Neutral Point Clamping (NPC) types available.

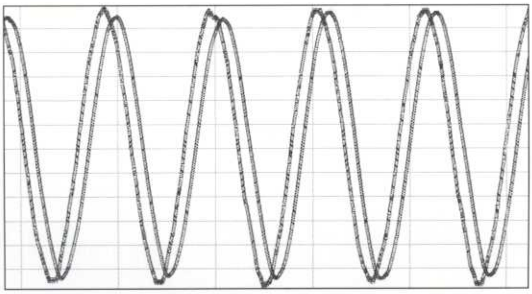
An NPC connected DC link can be used to improve motor loading capacity. The constant DC voltage is applied to the motor terminals using pulse-width-modulation or DTC. In the case of PWM this means that the frequency and amplitude of stator voltages can be controlled independently, while with DTC motor flux and motor torque are controlled directly.



Output filter

Some manufacturers provide a sine wave output filter. The combination of the NPC and sine wave filter can give an excellent output wave form.

Typical output voltage and current of a 4.16kV medium-voltage AC drive running at a frequency of 60 Hz.



With this waveform, problems of **voltage reflections** can be eliminated. Voltage reflections are a real concern at medium-voltage levels, because when a drive is retrofitted onto an existing motor, the condition or the quality of the insulation of that motor may not be known.

A voltage reflection occurs when a steep wave pulse is sent from a converter to the motor along the motor cable. Due to an impedance mismatch between the motor cables and the motor, that voltage can double in magnitude and it can damage the motor insulation with disastrous consequences.

Voltage reflections are avoided due to the near pure sine wave output provided by the filter. There are no steep wave pulses therefore voltage reflections are not a problem. This means there is no limitation on the cable length, the only limitation being that of voltage drop.

This makes drives with such output waveforms perfect for installations with long cable runs between motor and converter, for example, downhole pumping where there may be several kilometers of cable.

The output filter can also completely eliminate **common mode voltages** from the motor due to the earthing arrangement of the filter.

ADVANTAGES

- Operates on the robust cage induction motor
- For drives with sine wave output can retrofit onto existing motors without derating
- Full torque even at standstill and very low speed
- Input power factor near unity for entire speed range
- Reduced voltage stress on the motor insulation
- Virtually unlimited cable length
- Elimination of variable speed drive induced torque pulsations
- Quieter motor operation
- Low network harmonics
- High dynamic performance
- High drive system efficiency
- Small footprint

TYPICAL TECHNICAL DATA

TWO - LEVEL INVERTERS	
Power range:	up to 3400 kW
Motor voltage:	2.3 to 4.16kV
Frequency range:	0 to ± 200 Hz
THREE - LEVEL INVERTERS	
Power range:	up to 8000 kW
Motor voltage:	2.3 to 6.9 kV
Frequency range:	0 to ± 200Hz
Speed control range:	0 to 100%
Converter efficiency:	typically ≥ 98%

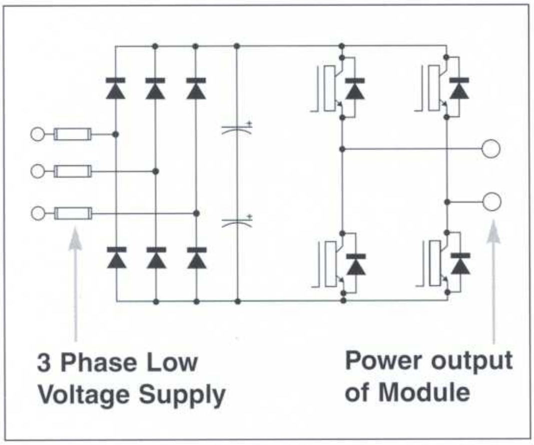
APPLICATIONS

- Standard drives for pumps, fans, compressors and conveyors (see part 1)
- High performance drives for mills, winches, cranes and other drives requiring high control accuracy or dynamic response
- High speed motor drives
- Extruders

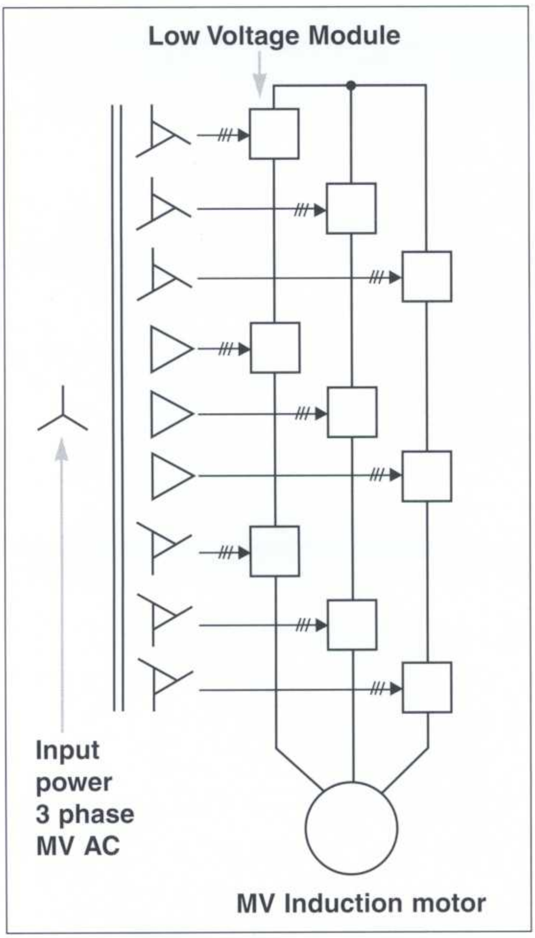
Multi-level Voltage-Source Inverter (derivative of VSI)

This system consists of multiple series connected low voltage cells which utilise low voltage IGBTs, fed from a multi winding input isolation transformer.

Low Voltage Module



Multilevel Topology



ADVANTAGES

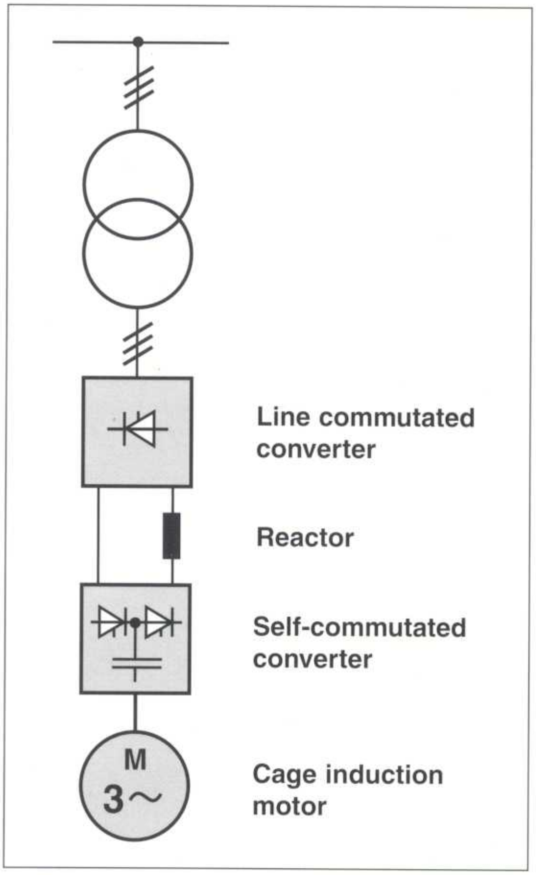
- Low network harmonics
- Quasi sine wave output although not sinusoidal

DISADVANTAGES

- Very high parts count gives low inherent reliability
- Additional low voltage cell by-pass arrangement may be required to ensure availability
- Has a large footprint compared to standard drives

Current-Source Inverter (CSI)

The system consists of a Current Source Inverter with a DC current link. It contains a controlled (line commutated) rectifier on the line side, a DC link with a reactor, and a self-commutated inverter on the motor side which converts the direct current to adjustable frequency three phase current. The amplitude of the motor current is adjusted by the controlled rectifier, whereas the frequency, and thus motor speed, is controlled by the inverter.



ADVANTAGES

- Four quadrant operation
- Cost effective

DISADVANTAGES

- Continuous operation at very low speed is not always possible
- Power factor is not constant over entire speed range (poor power factor at low speed)
- DC link reactor introduces additional losses as well as a larger drive and higher cost

APPLICATIONS

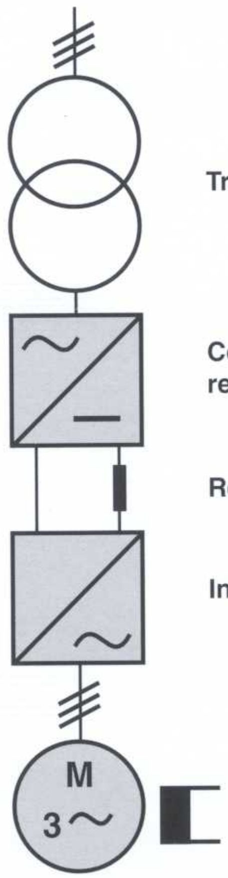
- Pumps
- Blowers and fans

TYPICAL TECHNICAL DATA

Power rating:	up to 8000kW
Output voltage:	2.3 to 6.9kV
Output frequency:	0 - ± 75 Hz
Converter Efficiency:	97%
Speed control range:	2 - 100%

Load Commutated Inverter (LCI)

A DC current source is formed from the line commutated controlled rectifier and a reactance. The Load Commutated Inverter (LCI) operates with variable machine voltage and frequency, switching the DC current to the machine winding. In this system, the synchronous machine behaves like a DC machine. The inverter operates as a static commutator. The control prevents the rotor from falling out of step. Thus, the machine is fully self controlled.



TYPICAL TECHNICAL DATA

Typical power range: (depending on power rating)	1- 80MW
Maximum speed:	7500 rpm
Speed control range:	(0) - 10 - 100%
Motor frequency:	0 - 125 Hz
Converter efficiency:	>99% 99 - 99.4% depending on power

ADVANTAGES

- Single motor drive for medium and high power ratings
- Suitable for synchronous machine with brushless or slipring excitation
- Inherent 4-quadrant operation
- Wide speed and power range

DISADVANTAGES

- Not suitable for use on standard squirrel cage induction motors
- May not be cost-effective for simple applications
- Large footprint compared to standard drives

APPLICATIONS

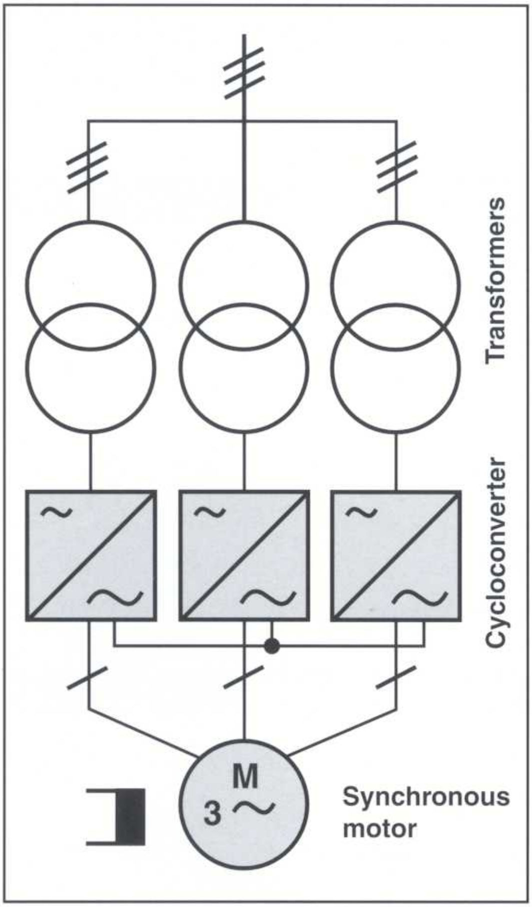
Suitable for continuously operating drives for:

- Fans and pumps
- High speed compressors
- Reciprocating compressors
- Wind tunnel fans
- Rolling mills
- Extruders
- Coupling of variable speed generators to constant frequency utility network

Cycloconverter

The drive is usually fed from a supply network via transformers. Each motor phase has its own converter, which consists of two anti-parallel six-pulse converters.

The cycloconverter operates as a three-phase current source. The stator and a cycloconverter converts the AC voltage, at line frequency, to an alternating voltage at load frequency, without any intermediate DC circuit. However, the load frequency is limited to 40% of the line frequency. Stator and excitation currents are controlled to ensure optimal performance of the drive, both statically and dynamically, over the entire frequency range.



TYPICAL TECHNICAL DATA

Typical power range:	
Low voltage	1.5 - 15 MW
High voltage	5.0 - 30 MW
Max. speed:	600/720 rpm for 50/60 Hz supply
Max. frequency:	20/24 Hz for 50/60 Hz supply
Speed range	± 0 - 100Hz
Motor frequency:	20 - 24Hz

ADVANTAGES

- 4-quadrant operation
- Motor cos phi = 1.0 is possible
- High stall and holding torque available
- Excellent performance at low speeds
- High dynamic overload capacity
- Field weakening range 1:3

DISADVANTAGES

- Limitation on maximum output frequency
- Power factor not constant over entire speed range
- May not be cost-effective on standard applications
- Has a large footprint compared to standard drives

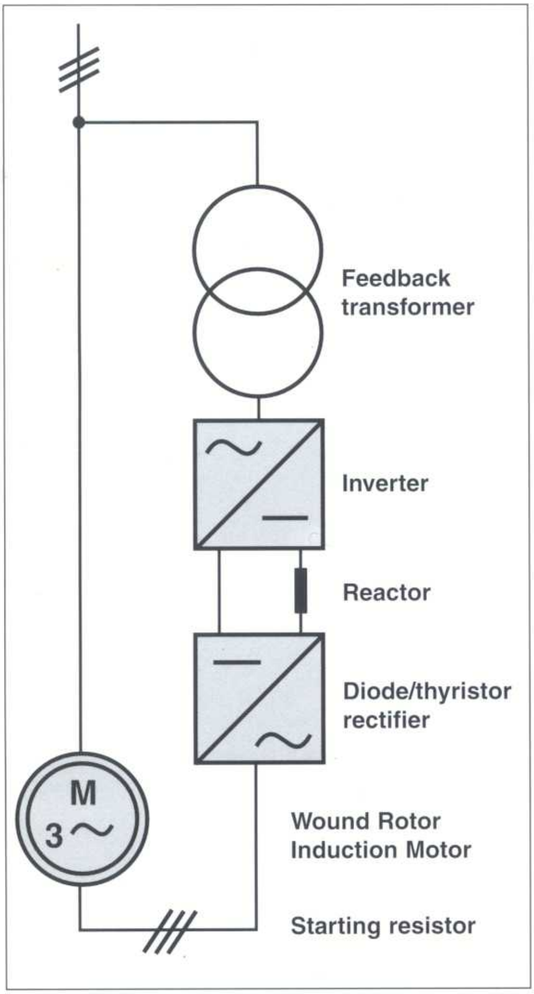
APPLICATIONS

- Rolling mills
- Propulsion drives for ships
- Ore and cement mills
- Mine hoists
- Wind tunnel fans

Cascade /Kramer/Slip Energy Recovery (SER) drive

The DC link converter consists of a three-phase diode rectifier bridge, which operates at slip-frequency and feeds rectified slip-power to a smoothing reactor and a line commutated inverter back to the AC supply network. The speed of the motor is controlled by adjusting the DC current.

The circuit without the DC reactor but with thyristors in the rotor-side rectifier gives a compact, efficient solution which is insensitive to supply line disturbances.



ADVANTAGES

- Cost effective because converter only needs to be dimensioned for feedback power
- High total efficiency
- Inherent by-pass (the motor can be started and run at constant speed, independent of the converter)
- Suitable for retrofitting of existing slip-ring motors

DISADVANTAGES

- Cannot be used on standard squirrel cage induction motors.
- Power factor not constant over speed range

TYPICAL TECHNICAL DATA

Power range:	0.5 - 5 MW (20) MW
Max. speed:	1500 rpm (50 Hz) 1800 rpm (60 Hz)
Speed control:	Typically 50-98% of synchronous speed

APPLICATIONS

- Fans and pumps
- Retrofit installation (existing slip-ring motor drives)
- Crushers and mills
- Wood chippers
- Compressors and blowers

Motor Control Platform

Introduction

Here, the different types of motor control platforms presently available are examined together with an insight into the advantages and disadvantages of each.

Pulse Width Modulation (PWM)

Also known as Scalar or V/F Control, PWM drives were one of the first to be developed. They supply frequency and voltage to the motor to produce torque and speed.

A PWM drive takes mains AC voltage and frequency, converts it to DC and then uses a Pulse Width Modulator to simulate a sine wave.

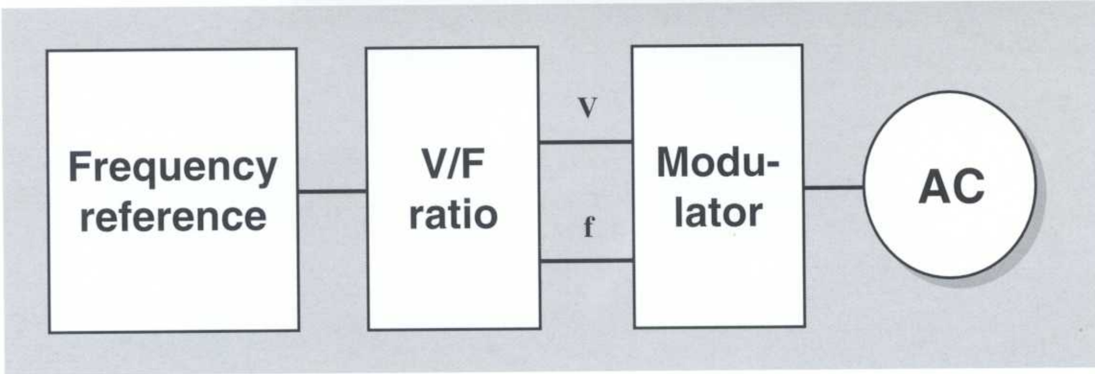
The sine wave is supplied to the motor, the voltage and frequency of the wave determining the torque and speed produced.

As torque and speed are controlled indirectly and the actual motor shaft position is not taken into account, speed and torque control is not as accurate as DC drives.

This makes producing high torque at low speeds (less than 10Hz) virtually impossible for PWM drives.

Also the electronics that produce the sine wave are complicated and the modulator reduces torque and speed response times.

Scalar Control



FEATURES

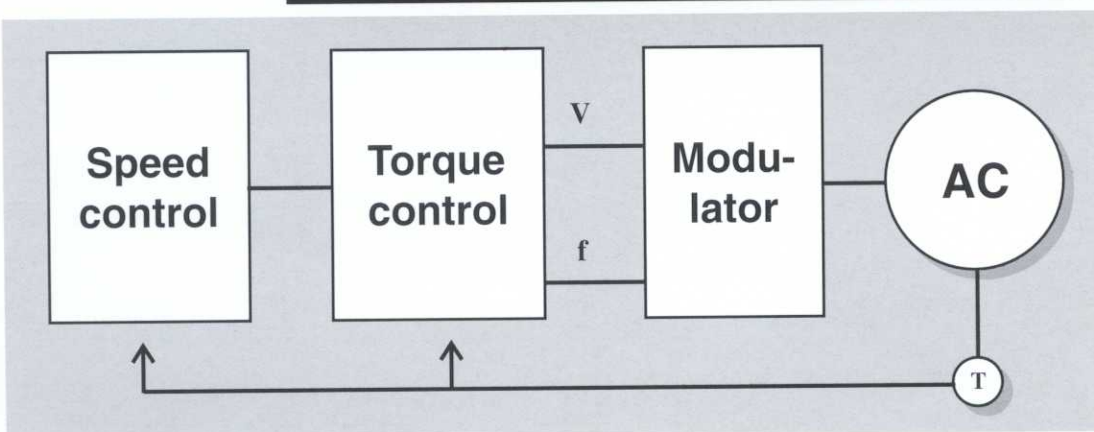
- **Control in short steps to avoid overshooting**
- **Modulator introduces additional delay in the control loop**

AC motor control theory goes back to Scalar Control where a constant voltage and frequency ratio was used to keep the motor flux constant.

Also, Scalar Control needs an additional modulator that has a pre-defined switching pattern to control the switching of the power semiconductors.

A disadvantage of Scalar Control is that control of torque is not possible. The load dictates torque. Another disadvantage is that the modulator introduces a delay in the response time of the control system.

Flux Vector



FEATURES

- **Tachometer feedback required**
- **Modulator introduces additional delay in the control loop**

With the advent of Flux Vector control, indirect control of torque became possible. With Flux Vector control, motor flux and motor torque are controlled separately.

Flux Vector drives give a higher performance than PWM models. A disadvantage of Flux Vector control is that a separate speed feedback device is always needed between the motor and the control system and this adds to the drive's cost and reduces reliability. This is because the control system always needs to know the relative position of motor flux and data flux.

'Sensorless' or open-loop Flux Vector technology, developed to operate without an encoder, significantly reduces the cost of this type of drive while maintaining the high performance.

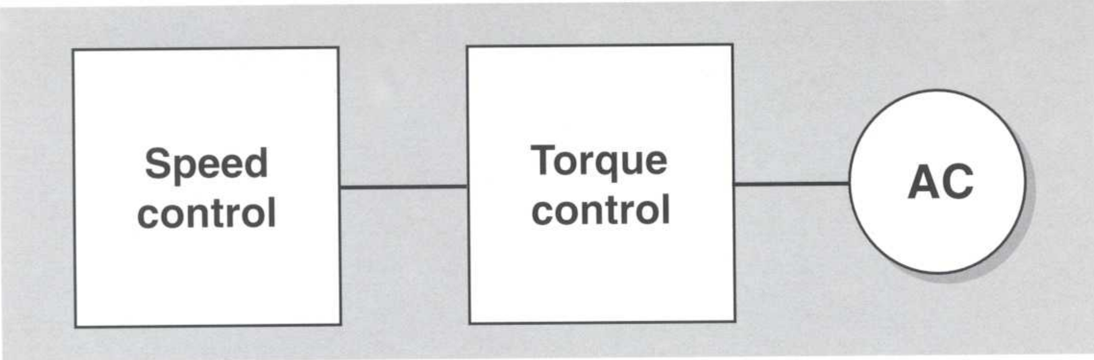
Open-loop models measure motor current as the motor operates and translates it into torque and flux, producing values using an in-built flux/torque look-up table. A control algorithm estimates motor slip and hence the speed and position of the motor shaft. The drive then calculates the voltage and frequency necessary to produce the required torque and speed from the motor slip and look-up values.

Sensorless Flux Vector drives give more accurate control of motor torque and speed than PWM models and can produce high torque at low speed.

At very low speeds (less than 5Hz), motor slip estimates are inaccurate. The voltage and current values required to produce the torque are therefore also inaccurate limiting the torque performance at very low speeds.

However, Flux Vector drives produce full torque at much lower speeds than PWM models - typically 3 to 5Hz. Their torque response and speed accuracy is several orders of magnitude greater than PWM.

Direct Torque Control (DTC)



FEATURES

- **Torque controlled by a single step**
- **No risk of overshoot with fast 25µs control loop**
- **Torque step rise time less than 10ms**

DTC is the newest technology to reach the market and controls motor speed and torque directly. This gives accurate speed and torque control, even at low speeds.

With DTC, motor flux and motor torque are used as primary control variables and direct torque control can be achieved with no speed feedback device. Thus, there is one less component to buy and one less component that can go wrong.

DTC features a highly accurate motor model, which produces signals that represent actual torque, flux and shaft speed. These actual values are compared with reference values in the model during a 25µs cycle. Only if the actual values exceed pre-set limits are the signals supplied to the motor.

As the drive only supplies energy to the motor when necessary and a modulator is not used, torque and speed response are ten times faster than other open loop technologies. Also, the 'just-in-time' switching means that less energy is used.

For medium-voltage AC drives, DTC provides the ability to control torque in the fastest way known today. This is major advantage for systems that require high dynamic performance and ensures that the system is always under control.

DTC brings some major performance benefits.

- **No modulator, therefore no fixed switching pattern - this reduces motor audible noise.**
- **Static speed control error is only from 0.1 to 0.5% of** nominal speed. This compares to 3% for Scalar Control.

- **Open loop torque step rise time** is less than 10 ms compared to the 100 ms for Scalar Control.

- **'Automatic start'** - DTC provides a vast improvement on the often called 'flying start', which provides the ability to catch a spinning load. For example, if a large fan is running and a drive trips due to a sustained voltage dip then the fan can take a long time - for example, up to half an hour - to slow down. If the voltage is restored quickly, then the 'automatic start' features instantaneous synchronisation with the converter to the motor. A spinning load is caught instantaneously without the need to wait for the flux to decay.

- **Superior ability to withstand load changes** - High instantaneous overloads can be applied without tripping the drive. Because the control system is so fast, the DTC based drive knows what is happening in the motor and can act on it quickly. This provides a high degree of motor protection.

Summary

This Technical Guide highlights the considerations that need to be given when selecting a medium-voltage AC drive.

It focuses on a significant new development within the medium-voltage drive arena - a "standard" solution, as opposed to an engineered solution. (See part 1 of this Technical Guide series for definitions of each type).

When choosing the right solution for an application, consideration must be given to the drive's electrical configuration (referred to as the topology) and the type of motor control platform used.

The right combination of topology and motor control platform can help alleviate many traditional problems associated with medium-voltage AC drives. These include common-mode voltages, voltage reflections, torque pulsations and poor torque and speed performance.

Written and edited by: Ewan Morris, ABB Industrie AG, in conjunction with David Armitage.

ABB Switzerland Ltd
Medium Voltage Drives
CH-5300 Turgi / Switzerland
Tel +41 58 589 27 95
Fax + 41 58 589 29 84