DC or AC Drives?

A guide for users of variable-speed drives (VSDs)
The annual growth rate for variable-speed drives (abbreviated to VSDs in the following text) is approx. 6%, while the growth rate for AC drives is around 8% p.a., with the market's volume for DC drives remaining more or less stable.

This overview is intended to outline to users, plant managers, industrial design engineers or the persons responsible for a particular process the features offered by DC drives as compared to AC drives.

Handling drive jobs: DC or AC drives?

Digital microprocessor-controlled power converter technology, both for DC and AC drives, has now reached a level of technical sophistication which (in purely technological terms) enables almost any drive job to be handled both with DC and AC drives. Nevertheless, the conventional DC drive (in both its 1-quadrant and 4-quadrant variants) will continue to play an important role, for technical and physical reasons alike: when dynamic drives with a constant load torque and stringent requirements for overload withstand capability throughout a large speed setting range are involved.

Main criteria for the user

The first thing a user should do is to objectively check out the options currently available in DC and AC drive technology for his/her specific requirements/processes.

The main criteria applying for this check are:

A Total purchase costs for the VSD system(s)
B Current operating costs:
   - maintenance
   - process costs/efficiency levels, etc.
   - space requirements
C Technological/Innovative aspects:
   - dynamic response, ramp-up time;
   - 4-quadrant operation; EMERGENCY STOP, etc.
   - space requirements; weight
   - up-to-the-future DC technology
D Operational dependability, availability of the drives:
   - international regulations like IEC, EN, CE-EMC; CSA, UL, etc.
   - environmental conditions; degrees of protection
   - service; 'on-the-spot' repairs
E Any effects on the surroundings:
   - supply network
   - EMC
F Required space for converter and motor
G Heat dissipation from the control room

Comparison of the basic characteristics of DC and AC drives in industrial applications

The following comparison of basic DC-drive and AC-drive characteristics covers only 6-pulse 3-phase thyristor drives with externally excited DC motors [referred to below as DGs], and 3-phase frequency converters in PWM design (voltage source converters with Pulse Width Modulation) with asynchronous three-phase motors [referred to below as AGs], in the following typical rating categories:

<table>
<thead>
<tr>
<th>Drive component</th>
<th>Typical rating category of ABB ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC thyristor converter</td>
<td>$P_{AC} = 11 \text{ kW} ... 5200 \text{ kW}$; $U_{AC} = 200 \text{ V} ... 1190 \text{ V}$</td>
</tr>
<tr>
<td>DC motor</td>
<td>5 kW/6000 rpm ... 3200 kW/900 rpm</td>
</tr>
<tr>
<td>AC PWM converter</td>
<td>$P_{AC} = 0.5 \text{ kVA} ... 2500 \text{ kVA}$; $U_{AC} = 380 \text{ V} ... 690 \text{ V}$</td>
</tr>
<tr>
<td>AC asynchr. motor</td>
<td>0.75 kW/3000 rpm ... 2000 kW/1500 rpm</td>
</tr>
</tbody>
</table>

DC Drive

AC Drive

In a first superficial comparison, hardly any significant differences can be found; however, when scrutinized more closely, differences in the drive features and in the physical method of functioning emerge.

The sections below cover the following points:

- the drive motor as the interface to the process
- the converter as power controller
- 4-quadrant drives
- any effects on the surroundings
- Modernization of existing DC drives
- ABB drives: for innovative future-compatibility
**Differences between DC and AC motors**

For general motor evaluation, many users adopt the following rather simplistic view: the DC motor is complicated and requires a lot of maintenance, which makes it expensive to run; it also has a lower degree of protection. The AC motor, on the other hand, is simple and sturdy; does not need much maintenance, is therefore less expensive, and possesses a higher degree of protection into the bargain. This categorization may well be true for many simple applications; it is nonetheless advisable to subject this sweeping verdict to more detailed scrutiny!

![Torque characteristic: operating ranges (basic depiction)](DC Drive)

**DC Drive**

The forced ventilation feature customarily used (approx. 85% of VSDs ≤ 250 kW) ensures good dissipation of the rotor losses originating in the DC motor.

![Torque characteristic: operating ranges (basic depiction)](AC Drive)

**AC Drive**

Surface ventilation customarily used (approx. 90% of VSDs ≤ 250 kW) for AC standard motors substantially reduces heat dissipation. At small speeds, dissipation of the rotor losses is hardly possible at all.

Typical applications for a constant torque over the entire basic speed range:

- wire-drawing machines, piston compressors,
- lift operators, aerial cableways, extruders, ...

Typical applications where the falling torque characteristic of AC motors is not a disturbance factor at small speeds (Fig. 4):

- pumps, fans, etc. with a quadratically increasing load torque ...
A comparison of operating characteristics of DC and AC motors shows that the direct-current motor is advantageous to the asynchronous motor for continuous operation at low speeds and for high setting ranges at constant power.

The possible overload in short-time duty depends not only on the motor parameters but to a high degree on the dimensioning of the associated DC thyristor converter / AC frequency converter as well.

The larger the speed range in which a motor can output its maximum power, the better the motor in question can be adapted to suit processes which require a constant drive power in a wide speed range.

Typical application: coilers

### Sizes, moments of inertia and ramp-up times:

The basic technical and design-related differences between DC and AC standard motors in magnetic-field formation and power-loss dissipation also entail different sizes (height) for the motors and different mass moments of inertia \( J_{\text{motor}} \) in km² for the rotors, with reference to the same torque, see the Comparison Table 1 below.
## Comparison Table 1: Mass moments of inertia for the rotors, sizes/shaft heights and weights for DC and AC Standard Motors (examples)

<table>
<thead>
<tr>
<th>Example</th>
<th>M_N Nm</th>
<th>P kW</th>
<th>n rpm</th>
<th>DC Motor</th>
<th>AC Standard Motor</th>
<th>AC Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Type</td>
<td>Type</td>
<td>Type</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>J_rotex kglm²</td>
<td>Shaft height H</td>
<td>Weight kg</td>
</tr>
<tr>
<td>1</td>
<td>71</td>
<td>15</td>
<td>2000</td>
<td>DMP112-4L</td>
<td>0.05</td>
<td>112</td>
</tr>
<tr>
<td>2</td>
<td>579</td>
<td>125</td>
<td>2000</td>
<td>DMP180-4LB</td>
<td>0.69</td>
<td>180</td>
</tr>
<tr>
<td>3</td>
<td>1570</td>
<td>329</td>
<td>2000</td>
<td>DM1225S</td>
<td>3.00</td>
<td>225</td>
</tr>
<tr>
<td>4</td>
<td>3565</td>
<td>560</td>
<td>1500</td>
<td>DMA+513S</td>
<td>10.68</td>
<td>315</td>
</tr>
</tbody>
</table>

1. Available in version IC37
2. Cooling system IC88W

DC motors have a significantly lower shaft height H and weight than do AC motors, with the mass moment of inertia of the rotor \( J_{rotex} \) consequently being substantially smaller with DC motors as well. But this mass moment of inertia is an important variable for highly dynamic applications, such as test rigs, flying shears, and reversing drives, since it has a marked influence on the ramp-up time \( t_a \) and the motor's dynamic response in four-quadrant operation (driving and braking modes).

### Mass moment of inertia:

\[
J = \frac{1}{2} \times m \times r_s^2 \quad [\text{kgm}^2]
\]

### Ramp-up time:

\[
t_a = \frac{(J_{rotex} + J_{external}) \times \Delta n}{M_s \times 9.55} \quad [\text{sec}]
\]

Values obtained from empirical feedback:

#### Ramp-up time \( t_a \) for DC Motors with \( M_s = M_N \)

for: \( \Delta n = 2000 \) rpm

Ex. 1: DC Motor 15 kW / 71 Nm; shaft height H = 112

\( J_{rotex} = 0.161 \) kglm²; same value as AC Motor

\[
t_a = \frac{(0.05 + 0.161) \times 2000}{71 \times 9.55} = 0.619 \text{ sec}
\]

Values obtained from empirical feedback:

#### Ramp-up time \( t_a \) for AC Motors with \( M_s = M_N \)

for: \( \Delta n = 2000 \) rpm

Ex. 1: AC Motor 15 kW / 71 Nm; shaft height H = 180

\( J_{rotex} = \) motor moment of inertia = 0.161 kglm²

\[
t_a = \frac{(0.161 + 0.161) \times 2000}{71 \times 9.55} = 0.946 \text{ sec}
\]

### Table 2:

<table>
<thead>
<tr>
<th>Example</th>
<th>M_N Nm</th>
<th>P kW</th>
<th>n min⁻¹</th>
<th>J_rotex kglm²</th>
<th>t_a sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71</td>
<td>15</td>
<td>2000</td>
<td>0.161</td>
<td>0.619</td>
</tr>
<tr>
<td>2</td>
<td>579</td>
<td>125</td>
<td>2000</td>
<td>2.5</td>
<td>1.15</td>
</tr>
<tr>
<td>3</td>
<td>1570</td>
<td>329</td>
<td>2000</td>
<td>10</td>
<td>1.73</td>
</tr>
<tr>
<td>4</td>
<td>3565</td>
<td>560</td>
<td>1500</td>
<td>25</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Table 2: Ramp-up times \( t_a \) based on the above motor data in the basic speed setting range.
High speed setting range at constant power (field weakening operation or field control range):

For specialized drive jobs, like coiler drives, test rigs, winders and unwinders, etc., very large setting ranges at constant power are stipulated. In these cases, conventional field weakening operation with an externally excited DC machine makes implementation particularly cost-efficient. This means: the larger the speed range in which a motor can output its maximum power (length of the horizontal section of the characteristic in Fig. 5, from \( n_1 \) to \( n_2 \)), the smaller the overdimensioning factor can be kept \( \frac{P_{\text{nominal}}}{P_{\text{nominal}}} \).

Values obtained from empirical feedback:

A typical value for the field weakening range of DC Motors with a shaft height of 112 ... 225 mm in the rating category of 5 ... 360 kW (\( M \leq 2000 \, \text{Nm} \)) is 1 : 3.

The maximum value for the field weakening range at compensated DC motors with a shaft height of \( \geq 250 \, \text{mm} \) in the rating category of 125 ... 1400 kW (\( M = 2400 \ldots 24500 \, \text{Nm} \)) is 1 : 5.

Example: compensated DC Motor DMA + 280 K (see Fig. 5)

<table>
<thead>
<tr>
<th>Speed n (rpm)</th>
<th>( n_1 )</th>
<th>( n_2 )</th>
<th>( n_{\max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power P (kW)</td>
<td>0</td>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td>Torque (Nm)</td>
<td>2483</td>
<td>2483</td>
<td>827</td>
</tr>
</tbody>
</table>

Motor maintenance:

Today, depending on the application involved, the useful lifetime of brushes in DC motors is at approx. 7000 ... 12000 hours (h), thanks to the sophisticated collectors, carbon brushes and optimized field supply units used. Depending on the mechanical conditions involved, the relubrication intervals for the bearings of DC/AC motors may be shorter than the useful lifetime of the brushes in DC motors.

Degree of protection for motors:

The historical development of the DC motor as an electric variable-speed drive since the beginning of the twenties has meant that DC motors are customarily used with internal/forced ventilation (approx. 85% of VSDs \( \leq 250 \, \text{kW} \)).

For variable-speed AC drives, asynchronous standard motors have predominantly been utilized since the 70s/80s, which mostly feature surface ventilation (approx. 90% of VSDs \( \leq 250 \, \text{kW} \)). Thus the process of matching the three-phase standard motors to the requirements applying for variable-speed drives with AC converters has not yet been concluded.

The fact that AC motors with ratings of up to approx. 1400 kW are supplied in degree of protection IP 54 as standard is a tribute to their simple and sturdy construction. For drive jobs in hazardous areas, explosion-protected AC motors are used almost exclusively. This means that the AC motor has won itself a firm position and proved its practical utility most especially in those sectors of industry characterized by aggressive ambient conditions and a high degree of dirt and dust in the cooling air.

Weight and space requirements:

The DC motors' lower weight and smaller size (usual degree of protection IP 23) as compared to the AC motors (usual degree of protection IP 54) are crucial for applications where the motor has to be moved together with the load (e.g. for large-size cranes in the "trolley travelling winch"), or in systems where space is at a premium (drilling rigs, skilift installations, marine applications, printing presses, etc.).

Efficiency and operating point of DC and AC standard motors:

The motor constant makes it possible to design the nominal point of DC motors corresponding to the process requirements. However the efficiency of AC motors is better \( > 55 \, \text{kW} \); approx. 1 ... 4% depending on cooling method). DC motors are often utilized according to insulation class H. Standard AC motors are used to be utilized according to insulation class B. This results in a possible higher efficiency with AC motors.
Differences between DC thyristor converters and AC frequency converters

- **Commutation and energy conversion:**

  **DC thyristor converter**-block diagram
  (one-quadrant drives)

  ![Fig. 6](image)

  Current transfer from one thyristor branch to the following (commutation) begins with a firing pulse, and after that proceeds in line-commutated mode. This means that the voltage between the commutating mains phases has been polarized in such a way that the current in the newly fired thyristor rises and thus correspondingly reduces the current in the 'predecessor' down to zero. Thanks to line commutation, this turn-off process functions without any problems even when the DC thyristor converter is being heavily overloaded. This is why the thyristors do not have to be dimensioned for a drive's peak current but for the long-time r.m.s. current value.

  **AC frequency converter**-block diagram
  (one-quadrant drives)

  ![Fig. 7](image)

  ![Fig. 8](image)

  a) with GTOs (Gate Turn-Off Thyristors)

  b) with IGBTs (Insulated-Gate Bipolar Transistors)

  Although the AC converter (frequency converter) works in its input section as a line-commutated power converter as well, the direct current previously generated has to be 'converted' back into three-phase current in the downstream inverter bridge. Since DC voltage does not have any passages through zero, the switching elements (GTOs or IGBTs) cannot switch off under voltage control. Conversely, they have to be able to actively interrupt the output current. When a GTO or an IGBT switches off, the current passes to a free-wheel diode at the opposite DC voltage pole. A commutation routine of this kind does not run under voltage control, but is possible at any time irrespective of the line voltage involved.

**Result:**

The advantage of a user-selectable turn-on/turn-off point with AC frequency converters is offset by the following disadvantages when compared to DC thyristor converters:

- The commutation routines run faster and therefore generate a higher level of interference (HF interference in the motor voltage, EMC problem).
- More space required at comparable power.
Continued:

In the DC thyristor converter, there is only **one** energy conversion routine (AC ↔ DC).
In the AC frequency converter, there are two energy conversion routines (AC ↔ DC and DC ↔ AC), i.e. the power loss is more than double that of DC thyristor converters.

**Values obtained from empirical feedback:**

- **Power loss at DC thyristor converters** = 0.8% ... 1.5% with reference to the rated power;
- **Power loss at AC converters** = 2% ... 3.5% with reference to the rated power;
- **Space requirement for power converter cabinets as individual drives with reference to rated power (> 100 kW)**: DC ≈ 100%  ↔  AC approx. 130% ... 300%.

This results in an advantage for DC drives, whenever small space and low power losses are an important feature (Cost for air conditioning).

### 4-quadrant drives (reversing drives) for both directions of rotation:

In many drive applications and production processes, the drives have to be able to handle both directions of rotation (frequently in regenerative mode), and also have to execute reversal from driving to braking mode 'suddenly' or 'extremely gently'. Typical examples here are: skilifts, elevators, cranes, mine drives, shears drives, reversing drives, etc. Two solutions are available here which have proved their worth in sophisticated industrial drive applications.

**4-quadrant DC drive** capable of regeneration, with field reversal

![4-quadrant DC drive](image1)

**4-quadrant AC drive** with chopper and braking resistor, for intermittent operation, EMERGENCY STOP, etc.

![4-quadrant AC drive](image2)

**4-quadrant DC drive** capable of regeneration, for all requirements

![4-quadrant DC drive](image3)

**4-quadrant AC drive** with fully controlled thyristor input bridge, for regeneration, for all requirements.

![4-quadrant AC drive](image4)

**4-quadrant AC drive** with IGBT controlled power supply, for regeneration, for all requirements.

![4-quadrant AC drive](image5)
Output currents of the DC thyristor converters/AC frequency converters; noise generation in the motor; load on the winding insulation, and electromagnetic compatibility (EMC):

- **DC Thyristor Converter**
  6-pulse thyristor bridge

![DC Thyristor Converter](image)

- **AC Frequency Converter**
  Voltage source frequency converter with PWM (simplified basic depiction)

![AC Frequency Converter](image)

- **Motor current/noise generation:**
  The voltage fed to the motors consists of segments from the sinusoidal line voltage. The motor current is a direct current on which is superimposed an alternating component with 6-fold line frequency. Thanks to this configuration, the noise problems encountered with DC drives are extremely slight.

- **Oscillations of motor torque:**
  The oscillating torque \( f_{\text{oscill}} = 6 \times f_{\text{line}} = 300 \text{ Hz} \text{ or } 360 \text{ Hz} \) resulting from the current ripple is superimposed on the drive torque and generally exceeds the mechanical resonance frequencies of drive system by far. For this reason there will be no problems for applications like winders/untwinders, coating machines etc..

- **Motor voltage/winding insulation:**
  With DC drives, the maximum voltage encountered at the motor terminals is equal to the peak value of the line voltage \( U_N \cdot \sqrt{3} \).

- **EMC:**
  For the reasons mentioned above, the installation outlay required for reducing electromagnetic emissions (EMC guidelines) is comparatively slight with DC drives.

- **Motor current/noise emissions:**
  The noise emissions from AC drives are closely dependent on the clock process and the clock frequency selected in each case.

- **Relative harmonic content of the motor torque:**
  The pulsating torque resulting from the harmonic content of current and voltage (deviation from the ideal sin) is in amplitude and frequency very closely dependent on the working point and the functional principle of the converter concerned. The probability of sympathetic oscillations in the drive train (motor, clutch, transmission, mechanical components, etc.) is thus concomitantly greater (exception: converters from ABB with DTC control).

- **Motor voltage/winding insulation:**
  The output current from pulse-controlled AC converters with IGBTs or GTOs contains steep voltage rises, which in the case of lengthy cables (> 10 m) may result in voltage peaks of up to twice the motor's rated voltage. This leads to additional stress on the cables concerned, and above all on the motor's insulation. It can be remedied, for example, by increased winding insulation or additional reactors in the motor's leads.

- **EMC:**
  The electro-magnetic emissions occurring with AC drives, together with cable-related interference, may render additional measures necessary.
Mains pollution:
The line currents of DC drives with a 6-pulse thyristor bridge will always contain, in addition to the fundamental wave, the 5th, 7th, 11th and 13th harmonics with empirical values of 22 %, 14 %, 9 %, 7.6 %, referenced to the fundamental wave. In the case of several DC drives operating simultaneously on the mains, the different phase sequences of the harmonic currents will produce a 'statistical improvement' in the level of mains pollution.

Due to the dimensioning method adopted for the smoothing inductors, harmonic currents with contents of 40 %, 14 %, 9 % and 7.6 % must be anticipated with AC drives featuring a 6-pulse diode bridge in 1-quadrant drives. Due to the identical phase angle of the harmonic currents, several drives on the same mains can be regarded as one drive with the same total current. This also applies for thyristor bridges in 4-quadrant operation.

Input bridges with IGBT switching elements enable the low-frequency harmonics to be substantially reduced, but conversely create more high-frequency harmonics.

Reactive-power demand:
Both drive concepts (AC and DC) take reactive power from the mains. Its size is negligible in the case of AC drives, and is RPM-dependent below the rated speed with DC drives. The AC drive is the more favourable option here.

### Values obtained from empirical feedback
For DC drives, the value for $\cos \phi$ is in

- 1-quadrant applications: $\cos \phi = 0.8...0.9$
- 4-quadrant applications: $\cos \phi = 0.8...0.85$

For AC drives, the value for $\cos \phi$ is in

- 1-quadrant applications:
  - with diode bridge: $\cos \phi = 0.99$
  - with thyristor bridge and
  - with energy recovery into the mains: $\cos \phi = 0.9$

Modernization of existing DC drives
When it comes to the question of whether it is worth while modernizing an existing DC drive or less expensive to replace it entirely with an AC drive, there are also various arguments which need to be assessed:

Basically, there are several options available for a modernization job:
1. Replace the entire DC drive (converter and motor) by a new DC drive.
2. Replace only the converter cubicle, if the motor is still in good condition.
3. Replace the converter module by a modern digital unit.
4. Replace the old, analog drive electronics by new, digital electronics while continuing to use the power section (recommended only for ratings above 1 MW).
5. Replace the entire drive system with a new AC drive.

When answering the question of what approach constitutes the optimum solution in a particular case, the following main criteria are important:
- Will the requirements for the drive change in future (load requirements, environmental conditions)?
- In what condition are the individual components of the system (reliability, age, maintenance outlay)?
- How far will the supply conditions change in future?

Before a decision is made to modify a drive from DC to AC design, the following points should be taken into consideration:
- Outlay for new power cabling.
- Space requirements for converter cubicles.
- Dissipation of energy losses from the switchroom sufficient?
- Foundations, mounting for motor sufficient?
- Space requirement for new motor.
- Duration of conversion work.
Price comparison DC and AC drive systems
(unit + motor or complete switchgear cabinet + motor)

Based on the present-day development status of DC and AC drive engineering, and taking into account all the systems’ advantages/disadvantages mentioned above, the following guideline figures can be given:

1-quadrant drives <40...80 kW  ⇫  AC drives less expensive
4-quadrant drives >40...60 kW
(AC converter + braking resistor; see Fig. 10);  ⇫  DC drives less expensive
Regenerative 4-quadrant drives > 15 kW  ⇫  DC drives less expensive

Prospects: ABB drives – for innovative future-compatibility

Given the steadily growing drive market, we expect the market volume for DC drives to remain more or less stable during the upcoming years, a view confirmed by the latest market studies.

A comparison of the two drive systems in this short overview shows that the question of whether the DC drive or the AC drive is the right choice for any particular user is entirely dependent on the individual application involved.

If the following requirements have to be met, then the use of DC drives should be examined:

a) 4-quadrant operation with regeneration?

b) Continuous operation even at low speed?

c) Less heat generation in the control room?

d) Frequent acceleration and deceleration routines?

e) Wide speed setting range at constant power (>1:1.5)?

g) Degree of protection for motors ≤ IP54?
   No hazardous areas?

h) Is motor maintenance possible (accessibility)?

i) Is space at a premium for motors and control units?

The greater the number of ‘Yes’s in answer to these questions, the more urgently should you consider using a DC drive!

DC or AC is therefore the crucial question which must be examined and decided for every single project.

ABB’s drive philosophy groups under one roof both the tried-and-tested DC drives and the wide and successful range of AC drives, integrating them into a holistically planned drive control and operating concept.

This has already been implemented in the DCS 400 / ACS 400; DCS 500 and DCS 600 / ACS 600 ranges since 1994, continually optimized in line with the latest market and customer stipulations, and simplified for enhanced user-friendliness into the bargain.
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