ABB drives

Technical guide No. 8
Electrical braking

Power and productivity
for a better world™

Technical guide No. 8
Electrical braking

3AFE64362534 REV B EN 6.5.2011

Contents

Chapter 1 - Introduction

1.1 General

This guide continues ABB's technical guide series, describing the practical solutions available in reducing stored energy and transferring stored energy back into electrical energy. The purpose of this guide is to give practical guidelines for different braking solutions.

1.2 Drive applications map according to speed and torque

Drive applications can be divided into three main categories according to speed and torque. The most common AC drive application is a single quadrant application where speed and torque always have the same direction, ie, the power flow (which is speed multiplied by torque) is from inverter to process. These applications are typically pump and fan applications having quadratic behaviour of load torque and thus often called variable torque applications. Some single quadrant applications such as extruders or conveyors are constant torque applications, ie, the load torque does not inherently change when speed changes.

The second category is two-quadrant applications where the direction of rotation remains unchanged but the direction of torque can change, ie, the power flow may be from drive to motor or vice versa. The single quadrant drive may turn out to be two quadrants for example if a fan is decelerated faster than mechanical losses could naturally achieve. In many industries also the requirement for emergency stopping of machinery may require two-quadrant operation although the process itself is single quadrant type.

The third category is fully four-quadrant applications where the direction of speed and torque can freely change. These applications are typically elevators, winches and cranes, but many machinery processes such as cutting, bending, weaving, and engine test benches may require repetitive speed and torque change. One can also mention single quadrant processes where the power flow is mainly from machinery to inverter such as in a winder or an uphill to downhill conveyor.

It is commonly understood that from the energy saving point of view the AC motor combined with inverter is superior to mechanical control methods such as throttling. However, less attention is paid to the fact that many processes may inherently include power flow from process to drive, but how this braking energy could be utilised in the most economical way has not been considered.

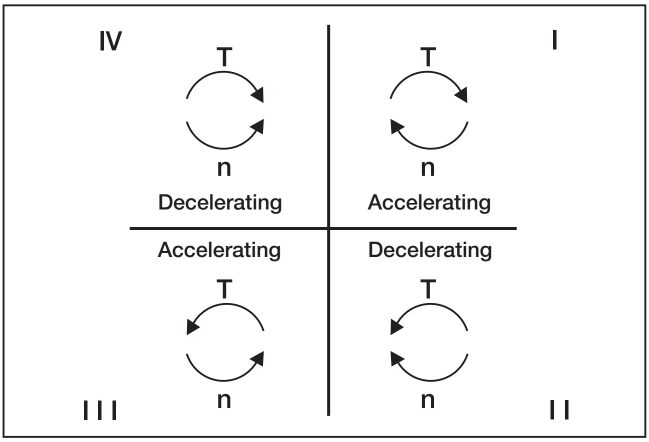

Figure 1.1 Drive applications map according to speed and torque.

Chapter 2 - Evaluating braking power

2.1 General dimension principles for electrical braking

The evaluation of braking need starts from the mechanics. Typically, the requirement is to brake the mechanical system within a specified time, or there are subcycles in the process where the motor operates on the generator side at constant or slightly varying speed.

It is important to note that devices used in electrical braking are dimensioned according to braking power. The mechanical braking power depends on braking torque and speed, formula (2.1). The higher the speed the higher the power. This power is then transferred at a certain specified voltage and current. The higher the voltage the less current is needed for the same power, formula (2.2). The current is the primary component defining the cost in low voltage AC drives.

In formula (2.2) we see the term $\cos\phi$. This term defines how much motor current is used for magnetising the motor. The magnetising current does not create any torque and is therefore ignored.

On the other hand, this motor magnetising current is not taken from the AC supply feeding the converter, ie, the current to the inverter is lower than the current fed to the motor. This fact means that on the supplying side the $\cos\phi$ is typically near 1.0. Note that in formula (2.2) it has been assumed that no loss occurs when DC power is converted to AC power. There are some losses in this conversion, but in this context the losses can be ignored.

$$P_{mech} = T * \omega = T * \frac{n}{60} * 2\pi \qquad (2.1)$$

$$P_{electrical} = U_{DC} * I_{DC} = \sqrt{3} * U_{AC} * I_{AC} * \cos\phi \qquad (2.2)$$

2.2 Basics of load descriptions

Typically loads are categorised as constant torque or quadratic torque type. Quadratic load torque means that the load torque is proportional to the square of the speed. It also means that the power is speed to the power of three. In constant torque applications, the power is directly proportional to speed.

2.2.1 Constant torque and quadratic torque

Constant torque:

C: constant

$$T_{load} = C \tag{2.3}$$

$$P_{load} = T * \omega = C * \omega \tag{2.4}$$

Quadratic torque:

$$T_{load} = C * \omega^2 \tag{2.5}$$

$$P_{load} = T * \omega = C * \omega^2 * \omega = C * \omega^3 \tag{2.6}$$

2.2.2 Evaluating brake torque and power

In the case of steady state operation (the angular acceleration α is zero) the motor torque has to make friction torque correspond proportionally to the angular speed and load torque at that specific angular speed. The braking torque and power need in respect to time varies greatly in these two different load types.

$$T_{motor} = -[J * \alpha + \beta * w + T_{load}(\omega)] \tag{2.7}$$

Let us first consider the case where the load is **constant torque type** and the drive system is not able to generate braking torque, ie, the drive itself is single quadrant type. In order to calculate the braking time needed one can apply the following equation. Please note that formula (2.7) underlines that the torque needed for inertia accelerating (or decelerating), friction and load torque is in the opposite direction to the motor torque.

$$0 = -[J * \alpha + \beta * w + T_{load}(\omega)] \tag{2.8}$$

In practice, it is difficult to define the effect of friction exactly. By assuming friction to be zero the time calculated is on the safe side.

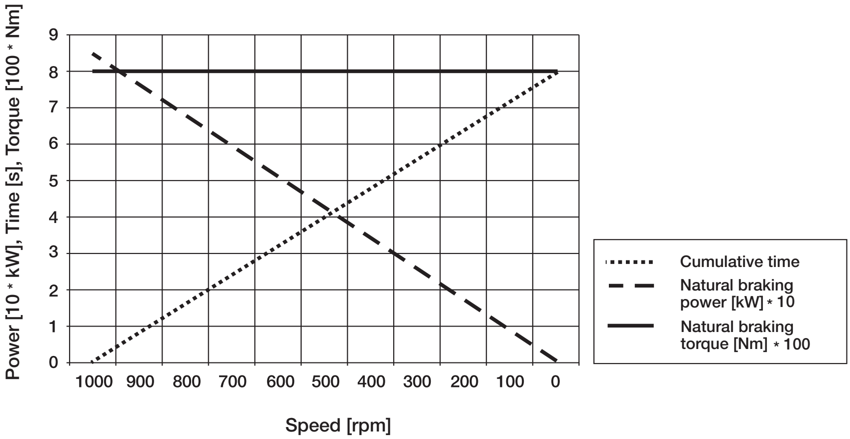

Figure 2.1 Cumulative braking time, braking load power and torque as a function of speed.

$$T_{load}(\omega) = J * \alpha = J * \frac{(\omega_{start} - \omega_{end})}{t} = J * \frac{(n_{start} - n_{end}) * 2\pi}{t * 60} \quad (2.9)$$

By solving t one ends up with the formula:

$$t = J * \frac{(n_{start} - n_{end}) * 2\pi}{60 * T_{load}(\omega)} \quad (2.10)$$

Assuming that the load inertia is 60 kgm^2 and the load torque is 800 Nm over the whole speed range, if the load is running at 1000 rpm and the motor torque is put to zero, the load goes to zero speed in the time:

$$t = J * \frac{(n_{start} - n_{end}) * 2\pi}{60 * T_{load}(\omega)} = 60 * \frac{(1000 - 0) * 2\pi}{60 * 800} = 7.85 \text{ s} \quad (2.11)$$

This applies for those applications where the load torque remains constant when the braking starts. In the case where load torque disappears (eg, the conveyor belt is broken) the kinetic energy of the mechanics remains unchanged but the load torque that would decelerate the mechanics is now not in effect. In that case if the motor is not braking the speed will only decrease as a result of mechanical friction.

Now consider the case with the same inertia and load torque at 1000 rpm, but where **the load torque changes in a quadratic manner**. If the motor torque is forced to zero the load torque decreases in quadratic proportion to speed. If the cumulative braking time is presented as a function of speed, one sees that the natural braking time at the lower speed, eg, from 200 rpm to 100 rpm, increases dramatically in comparison to the speed change from 1000 rpm to 900 rpm.

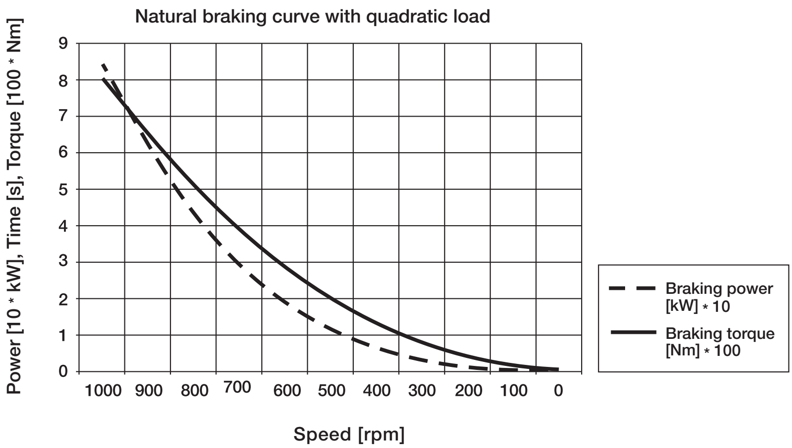

Figure 2.2 Natural braking curve for a 90 kW fan braking load power and torque as a function of speed.

A natural braking curve can easily be drawn based on the power and speed at the nominal point applying the formulas (2.5) and (2.6).

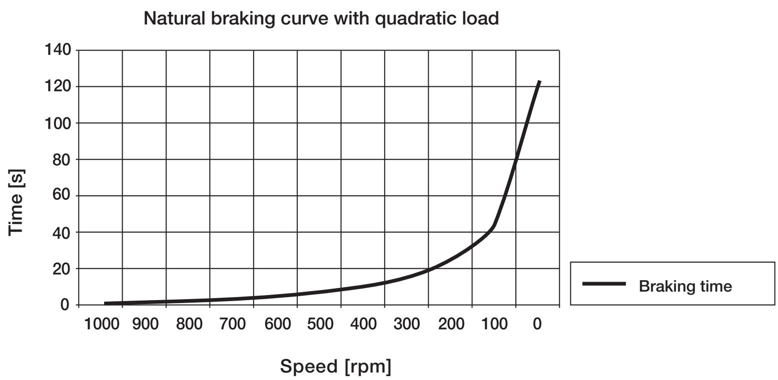

Figure 2.3 Cumulative braking time for, eg, a 90 kW fan.

Let us now consider the case where the requirement specifies the mechanical system to be braked in a specified time from a specified speed.

The 90 kW fan has an inertia of 60 kgm^2. The nominal operating point for the fan is 1000 rpm. The fan is required to be stopped within 20 seconds. The natural braking effect caused by the load characteristics is at its maximum at the beginning of the braking. The maximum energy of inertia can be calculated from formula (2.12). The average braking power can be calculated by dividing this braking energy by time. This value is, of course, on the very safe side due to the fact that the fan load characteristics are not taken into account.

$$W_{kin} = \frac{1}{2} * J * \omega^2 = \frac{1}{2} * J * \left(\frac{n}{60} * 2\pi\right)^2 = P * t \qquad (2.12)$$

$$P = \frac{1}{2} * J * \left(\frac{n}{60} * 2\pi\right)^2 * \frac{1}{t} =$$

$$\frac{1}{2} * 60 * \left(\frac{1000}{60} * 2\pi\right)^2 * \frac{1}{20} = 16.4 \text{ kW} \qquad (2.13)$$

When the braking chopper is dimensioned for this 16.4 kW value and the motor braking capability at a higher speed is far more than 16.4 kW, the drive has to include a supervision function for maximum regeneration power. This function is available in some drives.

If one wants to optimise the dimensioning of the brake chopper for a specific braking time one can start by looking at figure (2.3). The speed reduces quickly from 1000 to 500 rpm without any additional braking. The natural braking effect is at its maximum at the beginning of the braking. This clearly indicates that it is not necessary to start braking the motor with the aforementioned 16 kW power in the first instance. As can be seen from figure (2.3) the speed comes down from 1000 rpm to 500 rpm without any additional braking within less than 10 seconds. At that point of time the load torque is only 25% of nominal and the kinetic energy conserved in the fan is also only 25% of the energy at 1000 rpm. If the calculation done at 1000 rpm is repeated at 500 rpm, it can be seen that the braking power in order to achieve deceleration from 500 rpm to 0 rpm is appr. 8 kW. As stated in previous calculations this is also on the safe side because the natural braking curve caused by the load characteristics is not taken into account.

To summarise, the target for a 20 second deceleration time from 1000 rpm down to 0 rpm is well achieved with a braking chopper and resistor dimensioned for 8.2 kW. Setting the drive regenerative power limit to 8.2 kW sets the level of braking power to an appropriate level.

$$W_{kin} = \frac{1}{2} * J * \omega^2 = \frac{1}{2} * J * \left(\frac{n}{60} * 2\pi\right)^2 = P * t \quad (2.14)$$

$$P = \frac{1}{2} * J * \left(\frac{n}{60} * 2\pi\right)^2 * \frac{1}{t} =$$
$$\frac{1}{2} * 60 * \left(\frac{500}{60} * 2\pi\right)^2 * \frac{1}{10} = 8.2 \text{ kW} \quad (2.15)$$

2.2.3 Summary and conclusions

There are two basic load types: constant and quadratic load torque.

Constant torque application:

- The load torque characteristic does not depend on the speed. The load torque remains approximately the same over the whole speed area.
- The power increases linearly as the speed increases and vice versa.
- Typical constant torque applications: cranes and conveyors.

Quadratic torque application:

- The load torque increases to speed to the power of two.
- When the speed increases, the power increases to speed to the power of three.
- Typical quadratic torque applications: fans and pumps.

Braking power evaluation:

- The quadratic load characteristics mean fast natural deceleration between 50-100% of nominal speeds. That should be utilised when dimensioning the braking power needed.
- The quadratic load torque means that at low speeds the natural deceleration is mainly due to friction.
- The constant load torque characteristic is constant natural deceleration.
- The braking power is a function of torque and speed at that specified operating point. Dimensioning the braking chopper according to peak braking power typically leads to overdimensioning.
- The braking power is not a function of motor nominal current (torque) or power as such.
- If the load torque disappears when braking starts the natural braking effect is small. This affects the dimensioning of the braking chopper.

Chapter 3 - Electrical braking solution in drives

The modern AC drive consists of an input rectifier converting AC voltage to DC voltage stored in DC capacitors. The inverter converts the DC voltage back to AC voltage feeding the AC motor at the desired frequency. The process power needed flows through the rectifier, DC bus and inverter to the motor. The amount of energy stored in DC capacitors is very small compared with the power needed, ie, the rectifier has to constantly deliver the power needed by the motor plus the losses in drive system.

3.1 Motor flux braking

Flux braking is a method based on motor losses. When braking in the drive system is needed, the motor flux and thus also the magnetising current component used in the motor are increased. The control of flux can be easily achieved through the direct torque control principle (for more information about DTC see Technical guide No. 1). With DTC the inverter is directly controlled to achieve the desired torque and flux for the motor. During flux braking the motor is under DTC control which guarantees that braking can be made according to the specified speed ramp. This is very different to the DC injection braking typically used in drives. In the DC injection method DC current is injected to the motor so that control of the motor flux is lost during braking. The flux braking method based on DTC enables the motor to shift quickly from braking to motoring power when requested.

In flux braking the increased current means increased losses inside the motor. The braking power is therefore also increased although the braking power delivered to the frequency converter is not increased. The increased current generates increased losses in motor resistances. The higher the resistance value the higher the braking energy dissipation inside the motor. Typically, in low power motors (below 5 kW) the resistance value of the motor is relatively large in respect to the nominal current of the motor. The higher the power or the voltage of the motor the less the resistance value of the motor in respect to motor current. In other words, flux braking is most effective in a low power motor.

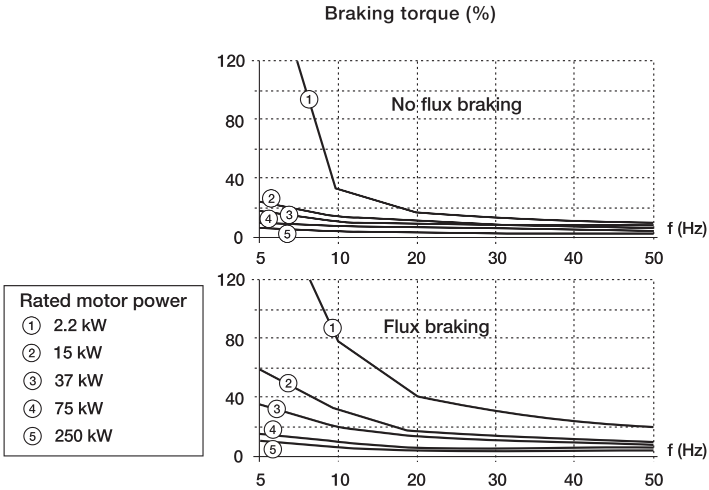

Figure 3.1 Percentage of motor braking torque of rated torque as a function of output frequency.

The main benefits of flux braking are:

- No extra components are needed and no extra cost, using DTC control method.
- The motor is controlled during braking unlike in the DC injection current braking typically used in drives.

The main drawbacks of flux braking are:

- Increased thermal stress on the motor if braking is repeated over short periods.
- Braking power is limited by the motor characteristics eg, resistance value.
- Flux braking is useful mainly in low power motors.

3.2 Braking chopper and braking resistor

3.2.1 The energy storage nature of the frequency converter

In standard drives the rectifier is typically a 6-pulse or 12-pulse diode rectifier only able to deliver power from the AC network to the DC bus but not vice versa. If the power flow changes as in two or four quadrant applications, the power fed by the process charges the DC capacitors according to formula (3.1) and the DC bus voltage starts to rise. The capacitance C is a relatively low value in an AC drive resulting in fast voltage rise, and the components of a frequency converter may only withstand voltage up to a certain specified level.

$$W = P * t = \frac{C * U_{dc}^2}{2} \tag{3.1}$$

$$U_{dc} = \sqrt{\frac{2 * W}{C}} = \sqrt{\frac{2 * P * t}{C}} \tag{3.2}$$

In order to prevent the DC bus voltage rising excessively, two possibilities are available: the inverter itself prevents the power flow from process to frequency converter. This is done by limiting the braking torque to keep a constant DC bus voltage level. This operation is called overvoltage control and it is a standard feature of most modern drives. However, this means that the braking profile of the machinery is not done according to the speed ramp specified by the user.

The energy storage capacity of the inverter is typically very small. For example, for a 90 kW drive the capacitance value is typically 5 mF. If the drive is supplied by 400 V AC the DC bus has the value of 1.35 * 400 = 565 V DC. Assuming that the capacitors can withstand a maximum of 735 V DC, the time which 90 kW nominal power can be fed to the DC capacitor can be calculated from:

$$t = \frac{C * U_{dc}^2}{2 * P} = \frac{5 * 10^{-3} * (735^2 - 565^2)}{2 * 90 * 10^3} = 6 \text{ ms} \tag{3.3}$$

This range of values applies generally for all modern low voltage AC drives regardless of their nominal power. In practice this means that the overvoltage controller and its ‘work horse’ torque controller of the AC motor has to be a very fast one. Also the activation of the regeneration or braking chopper has to be very fast when used in drive configuration.

3.2.2 Principle of the braking chopper

The other possibility to limit DC bus voltage is to lead the braking energy to a resistor through a braking chopper. The braking chopper is an electrical switch that connects DC bus voltage to a resistor where the braking energy is converted to heat. The braking choppers are automatically activated when the actual DC bus voltage exceeds a specified level depending on the nominal voltage of the inverter.

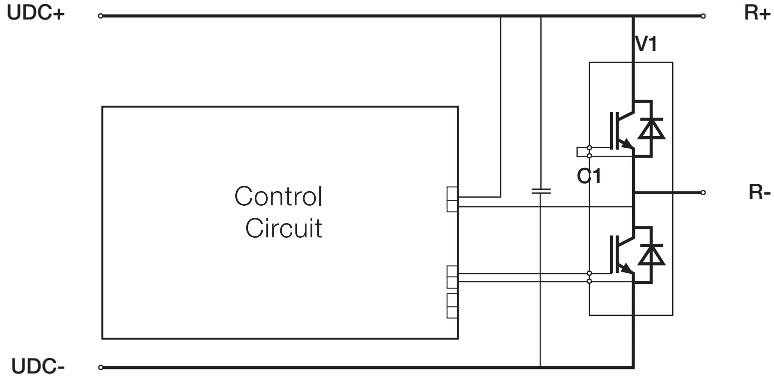

Figure 3.2 Circuit diagram example of braking chopper. UDC represents DC bus terminals and R the resistor terminals.

The main benefits of the braking chopper and resistor solution are:

- Simple electrical construction and well-known technology.
- Low fundamental investment for chopper and resistor.
- The chopper works even if AC supply is lost. Braking during main power loss may be required, eg, in elevator or other safety related applications.

The main drawbacks of the braking chopper and resistor are:

- The braking energy is wasted if the heated air can not be utilised.
- The braking chopper and resistors require additional space.
- May require extra investments in the cooling and heat recovery system.
- Braking choppers are typically dimensioned for a certain cycle, eg, 100% power 1/10 minutes, long braking times require more accurate dimensioning of the braking chopper.
- Increased risk of fire due to hot resistor and possible dust and chemical components in the ambient air space.
- The increased DC bus voltage level during braking causes additional voltage stress on motor insulation.

When to apply a braking chopper:

- The braking cycle is needed occasionally.
- The amount of braking energy with respect to motoring energy is extremely small.
- Braking operation is needed during main power loss.

When to consider other solutions than braking chopper and resistor:

- The braking is continuous or regularly repeated.
- The total amount of braking energy is high in respect to the motoring energy needed.
- The instantaneous braking power is high, eg, several hundred kW for several minutes.
- The ambient air includes substantial amounts of dust or other potentially combustible or explosive or metallic components.

3.3 Anti-parallel thyristor bridge configuration

In a frequency converter the diode rectifier bridges can be replaced by the two thyristor controlled rectifiers in antiphase. This configuration allows changing the rectifier bridge according to the power flow needed in the process.

The main components of the thyristor supply unit are two 6-pulse thyristor bridges. The forward bridge converts 3-phase AC supply into DC. It feeds power to the drives (inverters) via the intermediate circuit. The reverse bridge converts DC back to AC whenever there is a need to pass the surplus motor braking power back to the supply network.

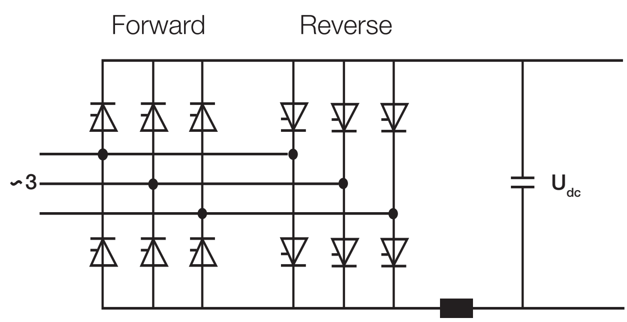

Figure 3.3 Line diagram of anti-parallel thyristor supply unit.

Only one bridge operates at a time, the other one is blocked. The thyristor-firing angle is constantly regulated to keep the intermediate circuit voltage at the desired level. The forward/reverse bridge selection and intermediate circuit voltage control are based on the measurement of the supply current, supply voltage and the intermediate circuit voltage. The DC reactor filters the current peaks of the intermediate circuit.

The main benefits of the anti-parallel thyristor bridge are:

- Well-known solution.
- Less investment needed than for an IGBT solution.
- The DC voltage can be controlled to a lower value than the network. In certain special applications this can be an advantage.

The main drawbacks of the anti-parallel thyristor bridge are:

- The DC bus voltage is always lower than AC supply voltage in order to maintain a commutation margin. Thus the voltage fed to the motor remains lower than the incoming AC. However, this can be overcome by using a step-up autotransformer in the supply.
- If the supplying AC disappears a risk of fuse blowing exists, due to the failure in thyristor commutation.
- The cosϕ varies with loading.
- Total harmonic distortion higher than in IGBT regenerative units.
- The current distortion flows through other network impedance and can cause undesired voltage distortion for other devices supplied from the point where voltage distortion exists.
- The braking capability is not available during main power loss.

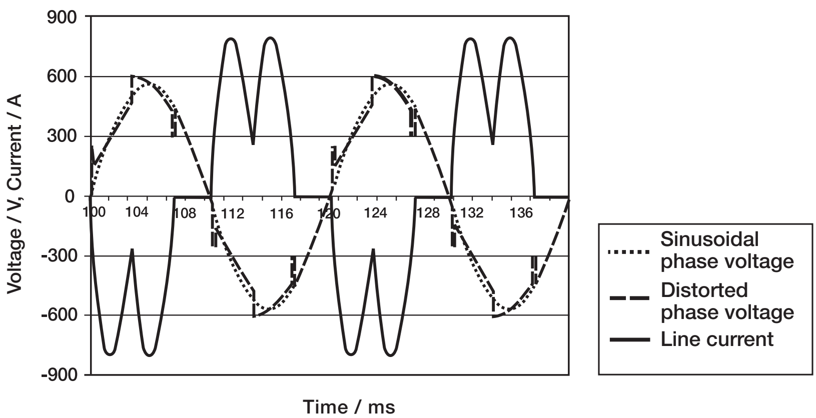

Figure 3.4. Example of anti-parallel bridge current and voltage waveforms during braking.

3.4 IGBT bridge configuration

3.4.1 General principles of IGBT based regeneration units

The IGBT based regeneration is based on the same principles as power transmission within a power network. In a power network several generators and load points are connected together. One can assume that at the point of connection the power network is a large synchronous generator having a fixed frequency. The input IGBT bridge of the drive (later line converter) can be considered as another AC voltage system connected through a choke to the generator. The principle of power transfer between two AC systems having voltage U and connected to each other can be calculated from figure (3.4).

$$P = \frac{U_{line} * U_{rec}}{X} \sin\delta \qquad (3.4)$$

The formula indicates that in order to transfer power between these two systems there has to be a phase difference in the angle between the voltages of the two AC systems. In order to control the power flow between the two systems the angle has to be controlled.

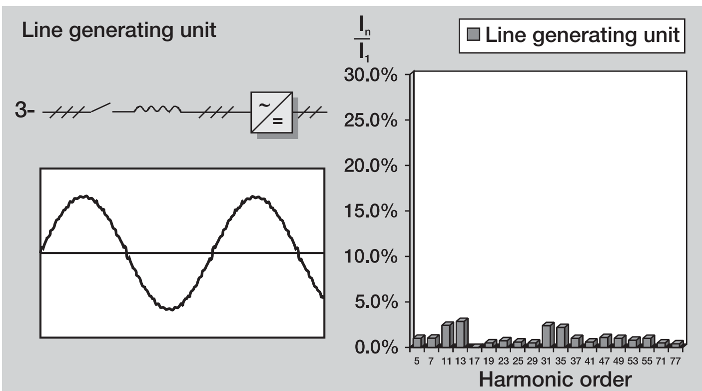

Figure 3.5. Typical line current waveform and harmonics of an IGBT line generating unit.

3.4.2 IGBT based regeneration - control targets

There are three general control targets in IGBT based regeneration units. The first one is to keep the DC bus voltage stable regardless of the absolute value of power flow and the direction of power flow. This ensures that inverters feeding AC motors can work in an optimum way regardless of the operation point thanks to a stable DC bus voltage. The DC bus voltage is stable when the power flow into the DC bus equals the power flow out of the DC bus. This control of appropriate power flow is achieved by controlling the power angle between the two AC systems.

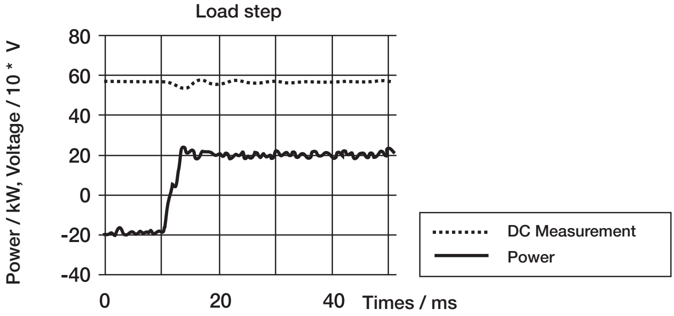

Figure 3.6. Fast change from regenerating to motoring operation. Note how stable the DC bus voltage is during this transition.

The second control target is to minimise the supply current needed, ie, to operate at cosφ = 1.0. This is achieved by controlling the output voltage of the line converter. In some applications it is desired that the IGBT line converter also works as an inductive or as a capacitive load.

The third control target is to minimise the harmonic content of the supply current. The main design criteria here are the impedance value of the choke and an appropriate control method.

3.4.3 Direct torque control in the form of direct power control

Direct torque control (DTC) is a way to control an AC motor fed by an inverter. The control principal turns IGBT switches on and off directly based on the difference between the actual AC motor torque and the user's reference torque (Technical Guide No. 1). The very same principle can be applied in a line converter controlling the power flow from power network to drive and vice versa. The power is torque multiplied by angular frequency, which in the network is constant, ie, controlling torque means also control of power flow.

$$P = \frac{U_l \, U_{lc}}{X} \sin\delta = |\underline{T}||\underline{\omega}| \tag{3.5}$$

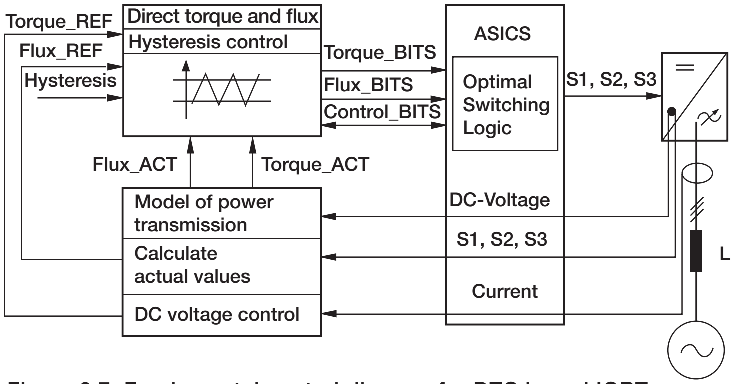

Figure 3.7. Fundamental control diagram for DTC based IGBT regeneration unit.

The DTC control method combined with IGBT technology contributes to a low amount of current harmonics. For that reason the IGBT supply unit can be used to replace single quadrant 12-pulse or 18-pulse supply configurations, which are typically used for reducing current harmonics on the supply side. An IGBT supply unit is therefore also a solution for those cases where current harmonics rather than the handling of braking energy is the issue.

The main benefits of an IGBT regeneration unit are:

- Low amount of supply current harmonics in both motoring and regeneration.
- High dynamics during fast power flow changes on the load side.
- Possibility to boost the DC voltage higher than the respective incoming AC supply. This can be used to compensate for a weak network or increase the motor's maximum torque capacity in the field weakening area.
- Full compensation of system voltage drops thanks to voltage boost capability.
- Possibility to control the power factor.
- Power loss ride through operation with automatic synchronisation to grid.
- DC bus voltage has approximately the same value during motoring or braking. No extra voltage stress on insulation of motor winding during braking.

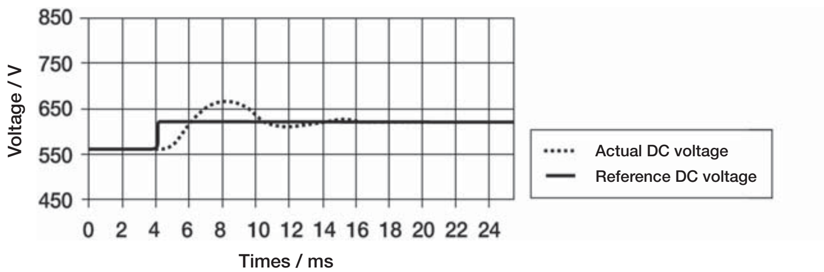

Figure 3.8. Boosting capability of supplying voltage.

The main drawbacks of an IGBT regeneration unit are:

- Higher investment cost.
- The braking capability is not available during main power loss.
- High frequency voltage harmonics due to high switching frequency. These several kilohertz voltage components can excite small capacitors used in other electrical devices. With appropriate design and arrangement of feeding transformers for different devices these phenomena are eliminated.

When to use an IGBT regeneration unit:

- The braking is continuous or repeating regularly.
- The braking power is very high.
- When space savings can be achieved compared to the braking resistor solution.
- When network harmonics limits are critical.

3.4.4 Dimensioning an IGBT regeneration unit

The supply current dimensioning of the IGBT unit is based on power needed. Let us assume that the motoring shaft power needed is 130 kW and braking power 100 kW. To dimension the IGBT supply unit the maximum value of motoring or braking power is selected, in this case 130 kW. The motor voltage is 400 V. The minimum value for the supplying network is 370 V.

In this case the voltage boost capability can be utilised; the DC bus voltage is raised to correspond to an AC voltage of 400 V. However, the required supply current is calculated based on the 370 level. Assuming that there are 5% system losses in the motor and drive, the total power needed from the grid is 136.5 kW. The supplying current can be calculated from the formula:

$$I_{in} = \frac{P}{\sqrt{3} * U_{in}} = \frac{136.5\ \text{kW}}{\sqrt{3} * 370\ \text{V}} = 213\ \text{A} \qquad (3.6)$$

The IGBT regeneration unit is selected based solely on the calculated current value.

3.5 Common DC

When a process consists of several drives where one motor may need braking capability when others are operating in motoring mode, the common DC bus solution is a very effective way to reuse the mechanical energy. A common DC bus solution drive system consists of a separate supply rectifier converting AC to DC, and inverters feeding AC motors connected to the common DC bus, ie, the DC bus is the channel to move braking energy from one motor to benefit the other motors. The basic configuration of the common DC bus arrangement can be seen from figure (3.9).

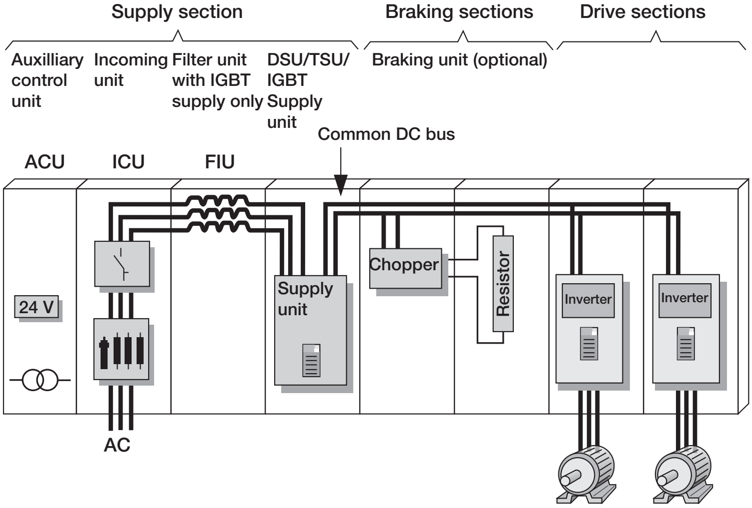

Figure 3.9. The basic configuration of the common DC bus solution.

The main benefits of the common DC bus solution are:

- Easy way to balance power flow between drives.
- Low system losses in conversion of braking energy thanks to common DC bus.
- Even if the instantaneous braking power is higher than motoring power the braking chopper and resistor do not need to be dimensioned for full braking power.
- If braking power is likely to be needed for long periods a combination of rectifiers can be used.

The main drawbacks of the common DC bus solution with single quadrant rectifier are:

- The instantaneous motoring power has to be higher than or equal to braking power.
- The braking chopper and resistor are needed if instantaneous braking power exceeds motoring power.
- If the number of motors is small the additional cost of a dedicated inverter disconnecting the device from the DC bus raises the investment cost.

When to use common DC bus solution with single quadrant rectifier:

- The number of drives is high.
- The motoring power is always higher than braking power or only low braking power is needed by the braking chopper.

Chapter 4 - Evaluating the life cycle cost of different forms of electrical braking

It has become increasingly important to evaluate the total life cycle cost when investing in energy saving products. The AC drive is used for controlling speed and torque. This basic function of AC drives means savings in energy consumption in comparison to other control methods used. In pump and fan type applications braking is seldom needed. However, modern AC drives are increasingly being used in applications where a need for braking exists.

Several technical criteria are mentioned above. The following examines the economic factors for different electrical braking approaches.

4.1 Calculating the direct cost of energy

The direct cost of energy can be calculated based, for example, on the price of energy and the estimated brak-ing time and power per day. The price of energy varies from country to country, but a typical estimated price level of 0.05 euros per kilowatt-hour can be used. 1 euro ~ 1 USD. The annual cost of energy can be calculated from the formula:

$$\text{Cost} = \text{Braking time (h/day)} * \text{Average braking power (kW)} * \text{price of energy (euros/kWh)} * 365 \qquad (4.1)$$

For example, a 100 kW drive is running 8000 hours per year and braking with 50 kW average power for 5 minutes every hour, ie, 667 hours per year. The annual direct cost of braking energy is 1668 euros.

4.2 Evaluating the investment cost

The required investment objects needed for different braking methods vary. The following investment cost components should be evaluated.

Braking chopper:

- The additional investment cost of braking chopper and resistor plus the cost of additional space needed for those components.
- The investment cost of additional ventilation needed for the braking chopper.

Thyristor or IGBT based electrical braking:

- The additional investment cost of thyristor or IGBT regenerative braking in respect to the same power drive without electrical braking capability.

Common DC bus:

- The additional investment cost of braking chopper and resistor including the space needed for those components if needed in a common DC bus solution.
- The investment cost difference between common DC bus solution and the respective single drive solution.

4.3 Calculating the life cycle cost

The life time cost calculation supports the purely economic decision in making an investment. The price level of energy as well as the price of drives varies depending on the country, utility, size of company, interest ratio, the time the investment is used and the overall macroeconomic situation. The absolute values of prices given in the following examples are solely used to illustrate the calculation principles.

Case 1 - Occasional braking

Consider the following application case:
The continuous motoring power is 200 kW at a shaft speed of 1500 rpm. In the event of an emergency stop command the application is required to ramp down within 10 seconds. Based on the experience of the process an emergency stop happens once every month. The inertia J of the drive system is 122 kgm^2. When the emergency stop is activated the load torque can be neglected.

Calculating the braking torque needed for the motor:

$$T = J * \frac{(\omega_{start} - \omega_{end})}{t} = J * \frac{(n_{start} - n_{end}) * 2\pi}{t * 60} =$$

$$122 * \frac{(1500 - 0) * 2\pi}{10 * 60} = 1915 \text{ Nm} \qquad (4.2)$$

The typical torque value for a 200 kW, 1500 rpm motor is about 1200 Nm. A normal AC motor instantaneously controlled by an inverter can be run with torque at 200% of nominal value. To achieve higher torque values a proportionally higher motor current is also needed.

The braking power is at its maximum at the beginning of the braking cycle.

$$P_{br,\,max} = T * \omega = 1915 * \frac{1500}{60} * 2\,\pi \approx 300 \text{ kW} \qquad (4.3)$$

The braking chopper and resistor have to withstand instantenously the current for a power of 300 kW. The average braking power is calculated below.

$$W_{kin} = \frac{1}{2} * J * \omega^2 = \frac{1}{2} * J * \left(\frac{n}{60} * 2\,\pi\right)^2 = P * t \qquad (4.4)$$

$$P = \frac{1}{2} * J * \left(\frac{n}{60} * 2\,\pi\right)^2 * \frac{1}{t} =$$

$$\frac{1}{2} * 122 * \left(\frac{1500}{60} * 2\,\pi\right)^2 * \frac{1}{10} = 150.3 \text{ kW} \qquad (4.5)$$

Cost of resistor braking:
The braking chopper needed is for a maximum braking power of 300 kW. If the drive has a power limitation function the braking resistor can be dimensioned according to the 150.3 kW. The additional cost of the braking chopper and resistor is 4000 euros. The braking resistor requires 0.4 m^2 additional floor space. The cost of floor space is 500 euros/m^2.

Due to the small total heating energy and emergency use of braking, the cost of additional cooling is considered negligible.

The total additional investment cost consists of:

- Braking chopper and resistor in cabinet, 4000 euros.
- Floor space 0.4 m^2 * 500 euros/m^2, 200 euros.

The total cost of wasted energy during one braking is:

$$\text{Cost} = \frac{10}{3600} \text{(h)} * \frac{300}{2} \text{(kW)} * 0.05 \text{ (euros / kWh)} = 0.02 \text{ euros} \qquad (4.6)$$

In this case the cost of braking energy is negligible.

Cost of 4Q drive:
The additional cost of a respective investment for electrical braking with anti-parallel thyristor bridge in comparison with a drive with braking chopper is 7000 euros. As expected, the energy savings cannot be used as an argument to cover the additional investment required.

Case 2 - Crane application

Consider following application case:
Crane with hoisting power of 100 kW. The crane needs full power on both the motoring and generating side. The longest hoist operation time can be 3 minutes. The average on duty time over one year for the hoist is 20%.

Cost of resistor braking:
The braking chopper and resistor have to be dimensioned for continuous 100 kW braking due to the 3 minutes maximum braking time. Typically the maximum braking chopper dimensioning is made for a braking time of 1 minute in 10 minutes.

– Braking chopper and resistor in cabinet 7800 euros.

The mechanical construction of the crane allows having cabinets with braking chopper. No extra cost due to floor space.

It is assumed that for 50% of the duty time the crane operates on the generator side, ie, an average 2.4 h/day. The total cost of wasted energy is:

$$\text{Cost} = 2.4\ (\text{h/day}) * 100\ (\text{kW}) * 0.05\ (\text{euros/kWh}) * 365 = 4380\ \text{euros} \qquad (4.7)$$

Cost of 4Q drive:
The IGBT 4Q drive is recommended for crane applications.

The additional investment cost for electrical braking with IGBT input bridge in comparison to drive with braking chopper is 4000 euros.

The direct payback calculation indicates that an additional 4000 euros investment brings the same amount of energy savings during the first year of use.

Case 3 - Centrifuge application

Consider the following application case:
Sugar Centrifuge with 6 pole motor 160 kW rating. The motor needs full torque for a period of 30 seconds to accelerate the charged basket to maximum speed of 1100 r/min, centrifuge then spins liquor off the charge for 30 seconds at high speed. Once the charge is dry motor decelerates the centrifuge as fast as possible to allow discharge and recharging.

In a batch cycle the charge, spin and discharge times are fixed, so the only opportunity to increase production is to increase the rates of acceleration and deceleration. This is achieved by using an IGBT 4Q drive as the DC link voltage can be boosted for operation in the field weakening range (1000 to 1100 r/min). This can save around 3 seconds per cycle, therefore reducing cycle time from 110 seconds to 107 seconds. This allows an increase in throughput meaning that the productivity of the process is improved. The cost premium for IGBT is 10%.

Chapter 5 - Symbols and Definitions

AC: Alternating current or voltage

B: Friction coefficient

C: Constant or coefficient

cosϕ: Cosine of electrical angle between the fundamental voltage and current

DC: Direct current or voltage

DPF: Displacement Power Factor defined as cosϕ1, where Ø1 is the phase angle between the fundamental frequency current drawn by the equipment and the supply voltage fundamental frequency component.

I: Current [Ampere, A]

J: Inertia [kgm^2]

n: Rotation speed [revolutions per minute,rpm]

P: Power [Watt, W]

PF: Power Factor defined as PF = P/S (power/voltampere) = I_1 / I_s * DPF (With sinusoidal current PF is equal to DPF).

T: Torque (Newton meter, Nm)

t: Time

THD: Total harmonic distortion in the current is defined as

$$THD = \frac{\sqrt{\sum_{2}^{40} I_k^2}}{I_1} \quad (5.1)$$

where I_1 is the rms value of the fundamental frequency current. The THD in voltage may be calculated in a similar way.

U: Voltage [V]

W: Energy [Joule, J]

ω: Angular speed [radian/second, 1/s]

Chapter 6 - Index

Contact us

For more information contact
your local ABB representative or visit:

www.abb.com/drives
www.abb.com/drivespartners

3AFE64362534 REV B EN 6.5.2011 #15654

Power and productivity
for a better world™