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SUMMARY

Long distance belt conveyors have always been a challenge for drive and control applications. There are several methods of applying the drive. Different drive systems have to be provided to suit the topographical conditions, the material to be transported, the environmental requirements and the operating methods. This article describes the drive system for a downhill conveyor between the quarry area and the raw material section of a cement plant in Switzerland. Because of the operational requirements the drive had to have an adjustable speed and should be capable of regenerating the power on the downhill section. A new technique, the Active Front End (AFE) technology, was applied and is described in detail. Nowadays all operating processes are monitored by sophisticated control systems. One of the big advantages claimed for this technology is that it is "extremely network friendly". The article also describes how all the environmental requirements are fulfilled by the use of a tube conveyor and examines the energy balance from the aspect of the active power taken out of the network and the regenerative power fed back into the network. ◀

ZUSAMMENFASSUNG

Auslegung und Betrieb von Gurtförderanlagen über große Förderlängen waren schon immer große ingenieurtechnische Herausforderungen sowohl für die Antriebsgestaltung als auch für die Steuerung. In Abhängigkeit von den topografischen Bedingungen, vom zu transportierenden Material, von der Erfüllung sowohl umwelt- als auch betriebstechnischer Anforderungen, können verschiedene Antriebssysteme eingesetzt werden. In diesem Beitrag wird für eine Gurtförderanlage mit einem abwärts fördernden Steckenabschnitt zwischen dem Tagebau und dem Rohmateriallager eines schweizerischen Zementwerks das Antriebssystem beschrieben. Aufgrund der betrieblichen Erfordernisse wurden die Antriebe mit veränderlicher Geschwindigkeit ausgelegt und sind für den abwärts fördernden Streckenabschnitt auch zur Energierückgewinnung geeignet. Dabei gelangte die neue, als Activ-Front-End-Technologie bezeichnete Antriebstechnik zur Anwendung, die im Detail beschrieben wird. Alle Betriebsabläufe werden heutzutage mit intelligenten Kontrollsystemen überwacht. Einer der großen Vorteile, die für die Anwendung dieses neuen Antriebssystems sprechen, ist seine große „Netzfreundlichkeit". Der Beitrag berichtet auch über die zahlreichen umwelttechnischen Auflagen, die erfüllt werden mussten und gewährt einen Blick auf die Energiebilanz, die sowohl die aktive Versorgung der Antriebe aus dem Netz, als auch die regenerative Energielieferung in das Netzwerk enthält. ◀

Active Front End technology (AFE) as applied to a downhill conveyor[*]

Activ-Front-End-Technologie (AFE) im Einsatz bei einem abwärts fördernden Gurtförderer

1 Introduction

Vigier Cement AG, a member of the Vicat Cement Group in France, has been operating a cement plant in the Berner Jura, Switzerland since 1891. The plant has a yearly production capacity of about 700 000 tonnes. In 2003 Vigier Cement opened up a new quarry area where the limestone and clay material is transported for a short distance with dumpers to the crushing station with a capacity of 800 t/h. The crusher in the quarry area is linked by a 3 km long downhill conveying system to the cement plant. A total difference in height of 280 m, at an inclination of up to 28 degrees, has to be overcome during the transport. The challenge when erecting the downhill conveyor was to minimize the number of single conveyors, and consequently the number of transfer stations, with part of the conveying taking place in a tunnel. The main conveying system consists of a combination of two conveyors, both of them with downhill configurations.

The first conveyor is of a tubular design, which makes it possible to handle a conveying capacity of up to 1 400 t/h even with a fall of up to 28 degrees. The second conveyor is designed as a troughed belt conveyor with a capacity of 800 t/h for normal operation and the ability to transport 1 000 t/h for a maximum of 10 min and 1 400 t/h for a maximum of 5 min. ❱ Fig. 1 shows most of the downhill section of the installation.

The belt has a total conveying length of 2 645 m and a height difference of 274 m with a maximal variable conveying speed of 3.1 m/s.

Figure 1: Downhill section of the conveyor installation

2 Conditions for obtaining an operating licence, and possible drive options for downhill conveying

Several options were available when the new quarry project started. Because environmental protection plays an important role in Switzerland several feasibility studies were carried out before the new quarry area was defined. The study resulted in a concept for the quarry and transport system.

It was clear from the very beginning that a belt conveyor had to be used for the material transport. There was no chance of obtaining an operating licence for transporting the limestone and clay with trucks because of the costs over the life-cycle of the quarry as well as the environmental impact involved. Part of the material transport had to take place inside a tunnel, also for environmental reasons. The climatic conditions meant that special attention had to be given to the robustness of the equipment for the transport system. The quarry area is situated 900 m above sea level, which causes very rough operating conditions, especially in the wintertime. Due to the low temperatures well below freezing and the large quantity of snow over a long period it was subsequently decided that part of the conveyor should be inside a tunnel and the rest should be covered.

Downhill conveying is defined as transportation where the braking energy is normally not lost or turned into heat, but instead is fed back into the network by regeneration. It is necessary to differentiate between two different operating modes, namely fixed speed and adjustable speed.

2.1 Fixed speed operation and regeneration of energy back to the network

Any fixed speed drive, such as a squirrel cage induction motor or a wound rotor motor, is characterized by its inherent behaviour as a generator as soon as the motor is energized, as is the case when the motor is connected to the network, and the speed caused by conveying the load downhill takes the motor revolutions above the synchronous speed.

In a fixed speed drive configuration it is not necessary to install any additional equipment for the motor to act as a generator. Below the synchronous speed the slip to the network frequency is negative, so the motor functions as a drive motor. It drives the load and draws energy from the network. When the load drives the motor above the network frequency, as in the case of a downhill conveyor, the slip will become positive. The motor then runs as a generator and feeds energy back to the network.

Under adjustable speed conditions the drive must have four-quadrant characteristics in order to run like a motor or a generator. Older configurations have used, and are still using, network input circuits equipped with thyristors. These input circuits are relatively simple, because they are network commutated. The operative function does fulfil the requirements in terms of adjustable speed and also of regeneration. However, if the network is disconnected during the regenerative period, i.e. if the MV breaker opens for some reason, then the equipment will lose the commutation and cause a short circuit in the input thyristor bridge. Short circuits always involve burnt fuses.

Modern configurations use an "Active Front End" (AFE) circuit. Equipment with this configuration does not have the negative behaviour mentioned with the thyristors. There are no burnt fuses if the system becomes disconnected from the network and the equipment will be ready again as soon as the power is restored.

2.2 Stopping the conveyor by braking the drive

2.2.1 Fixed speed drives
Squirrel cage induction motors have very restricted braking capabilities and are only used on smaller installations. The only options are either to switch the motor off and brake with a mechanical brake, or else brake with a reverse current. The latter procedure is not used very often because reverse-current braking applies a heavy reverse torque at the instant of switching over, and the belt may start to slip, with the result that the current to the network is higher than permitted.

The wound rotor motor has more options for controlled braking. This configuration operates with higher power, and works on a medium voltage level. The motor is equipped with a secondary starter and a DC injection brake. The braking torque can be adjusted to suit the requirements.

2.2.2 Adjustable speed drives
The modern state-of-the-art downhill configuration is based on an adjustable speed drive with four-quadrant (4Q) characteristics, which means acceleration and braking in the forward direction, and acceleration and braking in the reverse direction. With the 4Q drive system there is no change in polarity of the torque when the speed of a running drive is reduced to zero. The change in speed will always cause smooth reactions in the belt. The speed can be decreased

to zero. It is even possible to hold the position at zero speed with a 4Q drive.

A low voltage version is generally utilized for the smaller transport systems. MV equipment is used for larger downhill conveyors, with capacities in the range of 800 kW and above, especially if the belt conveyor is long. The energy can be regenerated to the network.

3 Case study from Cement Vigier

The first question when planning a drive system for a conveyor is whether it should be driven by fixed speed motors or variable speed drives. To answer this question, it is necessary to identify the additional capital costs for the variable speed drives, and compare them with the advantages achieved and with the operating and service costs. It is also necessary to compare the respective service lives of the conveying system, the belt, the mechanical components and the structure.

3.1 Basic requirements for belt conveyor systems
The belt is the most expensive and most exposed component of a conveyor. In addition to the selection of an adequate drive system, it is necessary to ensure that the stress on the belt is kept within the design limits. This basic requirement must be maintained for all possible operating conditions, including emergency situations.

The load sharing of the different drives has to be coordinated in such a way that all the associated drives develop a similar torque even under partial load conditions and during starting/stopping procedures, but especially under full load or in emergency situations. It has to be ensured that the torque peaks transmitted to the belt are never greater than 20 to 30 % of the required torque, regardless of whether such peaks occur in the acceleration, operational or deceleration phases. The drive system for the belt must be able to allow a maintenance speed of 10 % of the nominal speed in both directions. Torque peaks must be controlled and limited to a permitted magnitude for all the mechanical components such as gearboxes, couplings, shafts etc. Possible belt slipping has to be monitored.

The belt must be started and stopped very gently and in a controlled manner so that the belt is not overstressed. This can be achieved with an S-shaped acceleration and deceleration ramp. In cases where the belt conveyor is very long it may even be necessary to start the drives on the head end before the ones on the tail end in order to tighten the belt first.

The service speed is normally approximately 10 % of the nominal belt speed. A separate low-speed motor system is required if DOL motors are used. With the variable-speed drive system all speeds can be achieved with the same equipment.

3.2 Conveyor braking
Depending on the topology no braking during operation is required for horizontal conveying systems. If the terrain is ascending and descending it may be necessary to use partial braking while the belt is being loaded and unloaded. Downhill conveyors require continuous braking

Table 1:   List of the technical parameters for the three belt conveyors

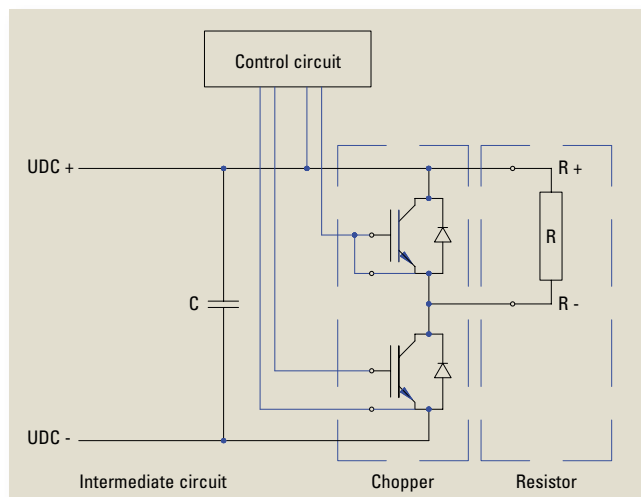| Parameter	Unit	Tube belt conveyor	Troughed belt conveyor	Tube belt conveyor
Distance between centres	m	244.46	2 397	550
Difference in altitude	m	-81	-193	+4.1
Max. slope	degrees	28	5	–
Nominal tube diameter	mm	400	–	400
Belt width	mm	1 600	1 200	1 600
Trough	–	–	Three-part, 40 degrees	–
Belt type	–	EP1000/4	ST1800	–
Idler diameter	mm	108	133	–
Installed motor power	kW	2 x 160	3 x 160	1 x 160; 1 x 55
Vertical curves	m	3 x 120	–	–
Horizontal curves	m	–	5 x 2000	–
Belt speed	m/s	3	3	3

Figure 2: Typical braking chopper configuration

during operation if the friction losses are smaller than the energy regenerated by the load.

Every downhill belt conveyor has to be equipped with an emergency brake. This has to be activated if one of the pull-ropes, and with it the corresponding emergency switch, is operated as well as in cases where excessive speed can occur. An electrical braking system cannot fulfil the safety standards because of possible power loss or defects in the electrical system. An electrical brake system is often used as the main brake during normal operation to decelerate the conveyor from high to zero speed in order to avoid excessive wear of the mechanical brake, while the mechanical disc brake takes over the shutdown and emergency situations. When sizing the mechanical brake it has to be borne in mind that it is necessary to brake the fully loaded conveyor from maximum speed to zero speed.

In cases where electrical braking is required, the motor acts as a generator and feeds energy into the DC link of the converter. Further braking by the motor then causes an increase in the DC link voltage since it is not possible to reduce the energy. However, the surplus energy has to be reduced if overvoltages are to be prevented. This can be achieved by different means:

❭ with a brake chopper and braking resistor in the DC link
❭ with a regenerative supply section.

The method with a braking chopper and braking resistor is uneconomical, because the surplus energy is converted into heat. The second option, using the recovery unit, allows all of the energy, with the exception of mechanical losses of the conveyor system and internal losses of the drive, to be fed back into the mains.

Either a six or twelve pulse diode bridge is normally used for the standard drive solution. Energy flow is only possible from the AC network to the converter and not vice versa. This energy has to be eliminated since the braking by a rotating motor under load will increase the voltage in the DC circuit of the converter. This can be achieved by heating a resistor. As soon as the DC circuit reaches a higher voltage level, a braking chopper will be activated and connect the DC bus directly to a resistor, the so-called braking resistor (❭ Fig. 2). It can be installed inside the cubicle or even outdoors. This installation is relatively simple and well known, but will waste

the energy. A braking chopper might be a solution if the braking is needed only occasionally, there is only a small amount of braking energy and electrical braking is needed in cases where the main AC supply is lost.

The regenerative drive based on an inverter at the supply unit is the opposite of the above-mentioned concept. It enables the braking energy to be fed back to the AC network so that the energy is not wasted, and provides an economic advantage. Modern IGBT-based regenerative units are able to control the DC bus voltage, regardless of the power flow and direction. The drive can be operated, if required, with cos phi = 1, which means that only active current is taken from the network and the harmonics are reduced to a minimal value (THD < 4 %).

4 Decision on the conveyor drive system

In DOL-operation with squirrel cage motors it is not possible to adjust either the starting and stopping torque or the acceleration and deceleration time as a function of the load. However, this is essential if the belt is to have a long service life. Even with slip ring motors, where the starting and stopping torques can be limited, it is not possible to achieve load-dependent starting and stopping times. This behaviour can only be achieved with an adjustable speed drive.

Conveyor systems are often installed at the end of a power line in a relatively weak network. Direct-on-line starting of a squirrel cage motor then causes a voltage drop in the mains, the magnitude of which depends on the mains short circuit power rating. In other words, the motor being started cannot rely on the full voltage, as this is also reduced by the voltage drop in the motor supply cable. In the case of two 160 kW motors, connected by a 100 metre long cable to a low-voltage network with a short-circuit power rating of 200 MVA, the voltage across the motor terminals will be reduced to about 87 % of its nominal value! A square-law relationship exists between the motor torque and the applied voltage, so that in this case less than 64 % of the accelerating torque is available. For a conveyor with a constant torque characteristic this means that it is even possible that the motor will not accelerate, and the rotor will be overheated and eventually destroyed.

An Active Front End frequency converter takes only active power from the mains. The torque of a squirrel cage induction motor is built up by the ratio of motor voltage and frequency (motor speed). The nominal torque can therefore be available from zero speed if the converter keeps the ratio of U/f constant during acceleration. To achieve a higher starting torque, the flux in the motor has to be increased by increasing the voltage during the starting phase. A typical starting current of a DOL motor is 7 x IN, and therefore much higher than for a converter drive with only one to two times I_N, depending on the required starting torque. The voltage drop will always be three to four times lower than with a DOL motor.

Under these conditions it is obvious that an adjustable speed drive with a frequency converter should be chosen.

5 Project engineering detail – calculations

The dimensioning of the motors and the creation of the drive system concept were based on the following requirements:

Table 2: Technical parameters for both belt conveyors

Parameter	Symbol	Units	Belt conveyor	
			tube	troug-hed
Input				
Capacity of the belt	Q_t	t/h	1400	1200
Frictional resistance of belt	C	–	0.6000	0.5200
Friction in pulleys 0.025 to 0.030	f	–	0.0281	0.0250
Belt weight/m incl. rotating parts	G_m	kg/m	151	80
Distance between centres	L	m	244	2397
Belt width (tube belt = diameter)	B	mm	400	1200
Height	H	m	-81	-193
Drum diameter	D	m	1.02	1.02
Belt speed	v	m/s	3.30	3.30
Gear ratio	i	–	25	25
Gear box efficiency	η	%	0.98	0.98
Output				
Required motor shaft power at full load	P	kW	-273	-449

- creation of the simulation and calculation model for all possible operating and loading conditions, including simulation of starting, stopping and emergency stopping scenarios,
- power trip under full, half and empty loading conditions,
- maximum allowed belt tension, in terms of mechanical belt stress and belt slip limits,
- maximum utilization of equal drive components and motor sizes in order to minimize the number of spare parts components,
- allowance for future increases in performance.

The result of the study led to the following concept:

Downhill conveyor 1:
Tube conveyor, with two motors on a common drum at the tail end.

Downhill Conveyor 2:
Troughed belt conveyor in the tunnel, with a total of three motors – two motors on the common first drum and one motor on the second drum.

All five motors were of the same power with the same physical dimensions.

Each drive system consisted of a frequency converter driving a squirrel cage motor of 160 kW, a disc brake between the motor and gear unit (the purpose of the disc brake is to hold the loaded belt when it is out of operation, when it is stationary, and, if there is a power dip, to brake the drive system safely to zero speed), a gear unit and a load cell to measure the torque, in order to avoid over-tension and stresses in the belt.

Under normal operating conditions the motors run at a pre-defined speed. The speed can be decreased below the nominal speed, for whatever reason, but can also be increased above the nominal speed in order to fill up an empty stockpile, etc. During the belt starting and stopping procedure the torque developed by the drive follows the S reference curve,

and no excessive belt stresses are produced. Special attention is given to the dynamical belt stress parameters during the starting and stopping procedures.

The drive power is determined by the following calculation:

$$P = \frac{C \cdot f \cdot L}{367 \cdot \eta} \cdot (3.6 \cdot G_m \cdot v + Q_t) + \frac{Q_t \cdot H}{367} \qquad (1)$$

Table 2 shows the technical parameters for both conveyors.

6 The drive solution

The results of the evaluation in the previous sections have basically shown a scheme with adjustable speed drives with the same type of motor. The following sections will evaluate which types of adjustable speed drive will be the most suitable.

6.1. Possible drive solutions
The drive solution for a conveyor, driven by several drives, can be either a single drive or a multidrive system. The single drive system consists of individual frequency converters, including rectifier and inverter, while the multidrive has a common rectifier section and DC-bus, but individual inverters, which can be controlled independently of one another. The decision as to whether it should be single drive or multidrive depends basically on the drive arrangement of the conveyor. The multidrive might be the preferred solution if several drives are used at the head and/or tail end. Otherwise, single drives can be used.

For the two conveyors of Ciments Vigier, the local situation made it possible to locate the electrical equipment house near the head end of the tubular belt conveyor and the tail end of the troughed belt conveyor. The two motors of the tubular belt conveyor are mounted on the tail end, which is located on the highest point, and is 250 m from the electrical equipment house. This configuration requires long motor cables. They have to be shielded three-core cables to fulfil the EMC requirement. The cost comparison showed that a centralized electrical equipment house, with only one 16 kV supply and transformer, was more economical than the decentralized solutions.

6.2 Basic principles of a voltage source frequency converter
As was shown earlier, there are very good reasons for controlling the belt conveyors by variable speed drives. The frequency converters considered here are of the voltage-source type. The system voltage is first rectified and then stored in a DC link, consisting mainly of capacitors. The inverter, with switchable semiconductor devices, subsequently converts the DC voltage back to AC to allow adjustment of its frequency and voltage. The speed of the connected cage induction motor is then varied in accordance with the applied frequency. The voltage also has to be varied as a function of the frequency to ensure that the induced flux remains constant. ❱ Fig. 3 shows the basic principle of a VVVF single drive frequency converter.

6.3. Variable speed drive solutions
6.3.1 Basic principles of single drive configuration
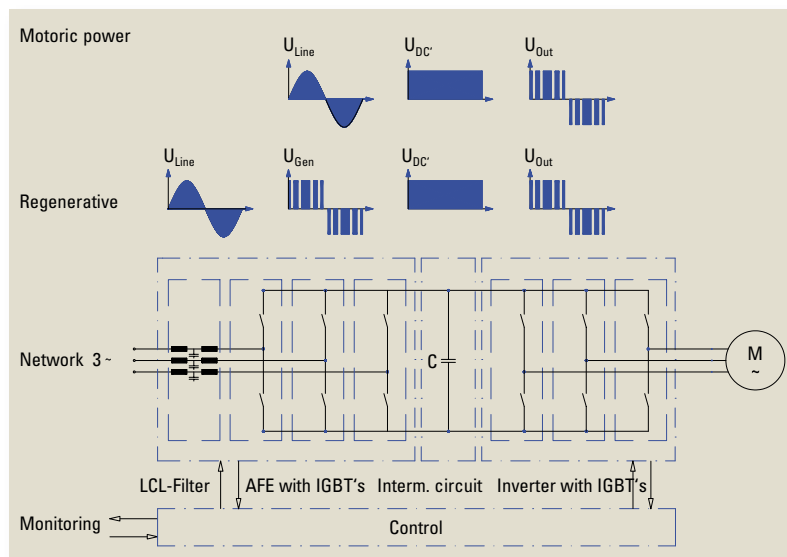Every individual frequency converter needs its own separate

Figure 3: Basic principle of a VVVF single drive frequency converter

feeder from an LV distribution system and supply cable. The space requirement depends on the number of drives used at the same location, but is usually larger for single drives than for a multidrive system. ❱ Fig. 4 shows the basic configuration of single frequency converter drives.

6.3.2 Basic principles of a multidrive system
Unlike individual drives, which have their own rectifier, DC link and inverter, the multidrive system generates the required DC voltage in a 'central' unit and feeds it into a common DC bus, to which the individual, independently operated, inverters are connected. All the desirable features of an individual drive are still retained. The multidrive, with common DC-bus, is the optimum drive solution for belt conveyor projects where several drives can be located in the same place. If the system contains more than one belt conveyor then the drives should be positioned at the transfer points, so that the drives of both conveyors can be connected to one multidrive. However, each system has to be studied individually to find the optimal design. ❱ Fig. 5 shows the basic configuration of a multidrive frequency converter.

The individual inverters connected to the common DC bus do not have to have the same power rating. On the contrary, a multidrive package can consist of drives of very different sizes. The power outputs as well as the motor speeds can therefore be different. The total installed motor rating should nevertheless not exceed the power rating of the central incoming feeder bridge. The terminal voltages of all the

individual motors should also be the same, since the variable converter output voltages are always taken off the common DC bus. Each inverter is connected individually to the overall control system to allow individual motor control. Each inverter module has the inherent capacity of a 4Q drive. With variable speed drives it is possible to make the adjustments that are necessary to meet the exact requirements of the operational process.

6.3.3 Technology for the supply section with Active Front End
In order to satisfy the increasing market demand for better network quality there has been tremendous development in the field of electrical variable speed drives, including optimization of the supply section. The new supply technology is generally called Active Front End (AFE), and consists of an intelligent IGBT modulation and LCL filter technology for generating an almost pure sinusoidal current waveform. When the harmonics up to the 40th are examined they result in a low harmonic content, and the IEEE 519 and EA G5/4 requirements can be fulfilled without additional external passive or active filters outside the supply section. At the same time the power factor is controlled and kept to 1 at any load point. The losses are lower because cos ρ = 1 and because of the sinusoidal waveform, so the peripheral equipment like the transformer, cables, etc. can be sized for the reduced load.

7 Harmonic distortion

All adjustable drive systems produce harmonics but at different magnitudes. No harmonic distortion is caused by a motor that runs at a fixed speed. The adjustable speed drive with a six pulse rectifier with frequency converter generates harmonics, causing distortion of either the voltage or current wave-shape. The amount of the current harmonic distortion depends on the type of supply section in the converter, while the voltage harmonic distortion depends mainly on the network configuration.

In the worst case the total rated power of the belt conveyor drives fed by the converter generates, via a six pulse diode bridge, a current harmonic distortion of the 5th harmonic of approx. 30 to 35 % on the primary side of the converter transformer. The power factor (cos ρ), however, is reasonable at
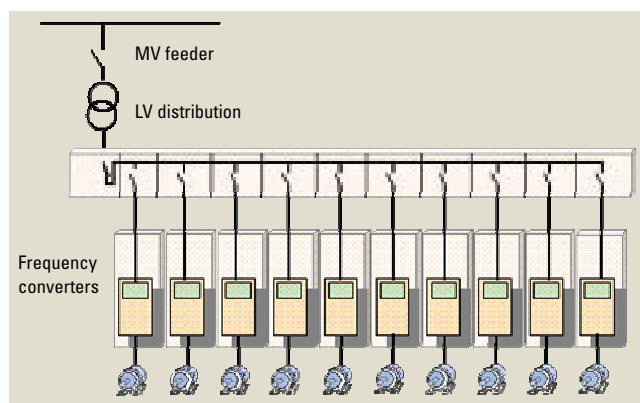

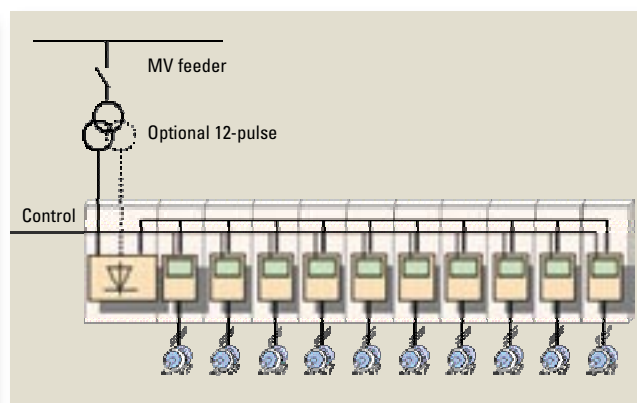Figure 4: Basic configuration of single frequency converter drives

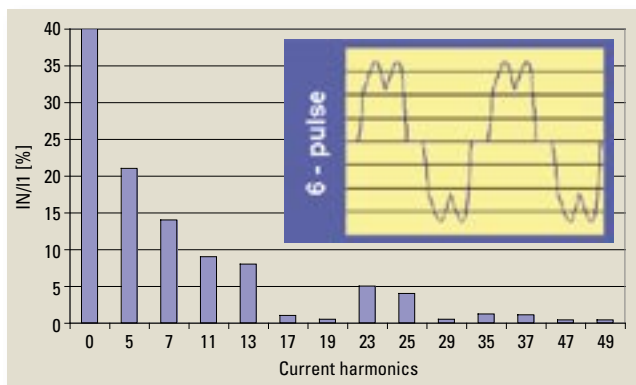Figure 5: Basic configuration of a multidrive frequency converter

Figure 6: Harmonics in a six pulse configuration

Figure 7: Harmonics with AFE configuration and the respective sin wave

about 0.96. ❭ Fig. 6 shows the current harmonics in a six pulse configuration and the respective sine wave.

It is common engineering practice in larger drive units to use two input diode bridges instead of one. A much better performance in terms of harmonic distortion can be achieved with two input bridges and transformer vector groups shifted through 30 degrees. The first harmonics that appear are the 11th and the 13th. In the worst case the twelve pulse diode bridge creates a current harmonic distortion of the 11th current harmonic of approximately 9% on the primary side of the converter transformer. The power factor cos ρ, however, is reasonable at about 0.96, i.e. the same as with the six pulse configuration.

The best option nowadays is a drive input circuit with the AFE configuration. In addition to using only a simple transformer without vector group shifting like the six pulse configuration, it also creates minimal harmonics, so that the standards of IEEE 519 and EN 50160 are not violated. The power factor (cos ρ) can be set at 1. ❭ Fig. 7 shows the current harmonics in an AFE configuration and the respective sin wave.

Theoretical values should always be taken with caution because, in actual practice, the situation may well be different. What really counts is when the measurement is carried out at the MV level of a busbar. Measurements were carried out at the Vigier Cement plant with and without the downhill conveyors equipped with multidrive and AFE. The measurements showed about the same level of quality of the network as the theoretical values.

As shown in Figs. 6 and 7, the harmonics created from the drives are of a different magnitude, shape and frequency spectrum in all three examples. Without any doubt, the AFE configuration shows the best results. Before imple-
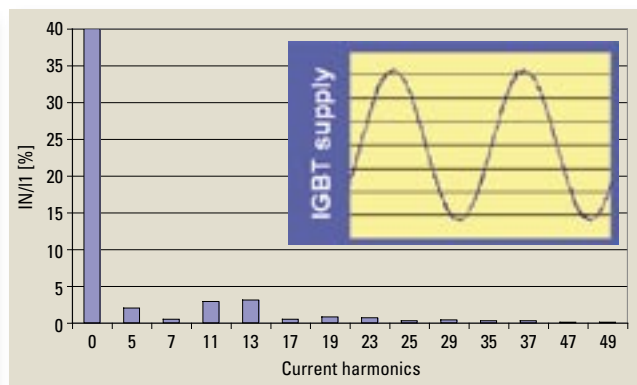
mentation of the drives, one of the other conditions was to carry out a review of the plant, register the harmonic content on the common plant AC bus. A comparison was then made during operation after the implementation of the new equipment.

❭ Table 3 shows the total harmonic distortion voltage (THD_u) on the 16 kV bus for several conditions before and after installation of the belt conveyors. From the two voltage measurements, the results show that all single harmonics as well as the THD_u are below limits of the standard EN 50160. As a percentage of the 50 Hz voltage, the maximum value of the THD_u was 1.680 % before and 1.490 % after connection of the AFE.

During normal operation the Active Front End can be used to compensate for the reactive power created by other equipment. This means it can operate with a power-factor-leading configuration of the order of about 140% of the required drive power. Within certain limits it could even be used as an online power factor regulator (❭ Fig. 8).

8 Ciments Vigier – optimized drive solution for the downhill conveyors

The downhill conveyors consist of one 2 397 m long troughed belt conveyor with three motors, each rated at 146 kW/500 V, at the head end (❭ Fig. 9) and one 245 m long tube belt conveyor with two motors, each rated at 135 kW/500 V, at the head end. The maximum possible designed power consumption is 708 kW at 1 500 min^{-1} (motor shaft) and the total required power consumption is 565 kW at 1 500 min^{-1} (motor shaft). The speed range with rated constant torque is 150 to 1 500 min^{-1} (motor shaft). All the motors are exactly the same, so that they are interchangeable and only one spare motor is needed.

The multidrive system is fed from a 16 kV network via a drive transformer rated at 1 000 kVA. The rectifier unit, type Active Front End (AFE), is dimensioned for 800 kW continuous shaft power. An individual inverter unit is provided for each of the five motors and connected to the common DC bus. Each unit is operated independently of the others and has its own serial interface to the process control system.

As shown in ❭ Fig. 10, each drive for the two downhill belt conveyors has its own inverter
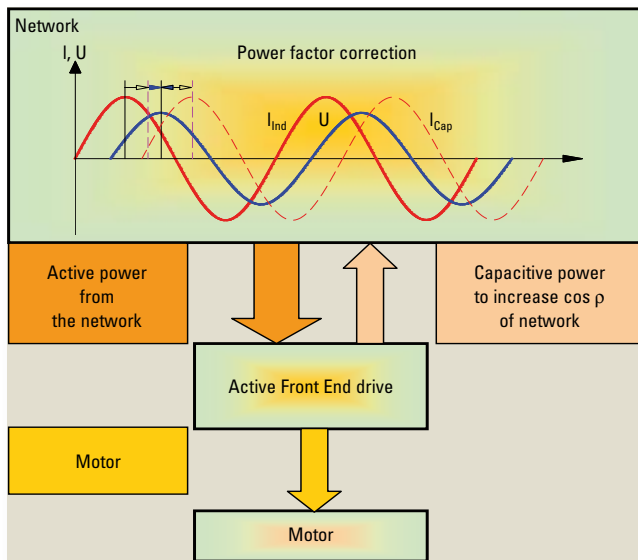
Table 3: Total harmonic distortion voltage before and after belt conveyor installation

	Before installation of belt conveyors [%]	After installation of belt conveyors [%]	Limits IEEE 519 [%]	Limits IEC [%]
Maximum of 10-minute values during complete measurement period	1.680	1.490	5	8
Average of 10-minute values during complete measuring period	1.007	0.882	–	–
Minimum of 10-minute values during complete measuring period	0.460	0.200	–	–

Figure 8: Relationship between power taken out of the network, power provided for the motor and capacitive power used for power factor correction

Figure 9: Configuration of the troughed belt conveyor tail end and drives

and motor. The inverters are connected to a single DC bus bar. This provides the inherent strength of the multidrive solution. Whenever power is being generated the power will be made available first on the DC bus bar, regardless of whether belt 1 is regenerative and belt 2 is operating as a motor (or any other operating configuration). Only the balance of the power sum will be taken out of the network or fed back to the network.

This very cost-saving and functional configuration was only possible because of the geographical situation.

9 Drive performance

❯ Fig. 11 shows the procedure for emptying and stopping the material transport. In detail this shows:

❯ crusher being stopped and downhill belt 1 being emptied
❯ downhill belt 1 being ramped down to zero speed in 15 s
❯ downhill belt 2 being emptied
❯ downhill belt 2 being ramped down to zero speed in 15 s

It can be seen clearly that the power of both belt conveyors is successively reduced from minus 324 to plus 130 kW during the belt-emptying process and the belt braking to zero speed. A short period of power regeneration can also be noted.
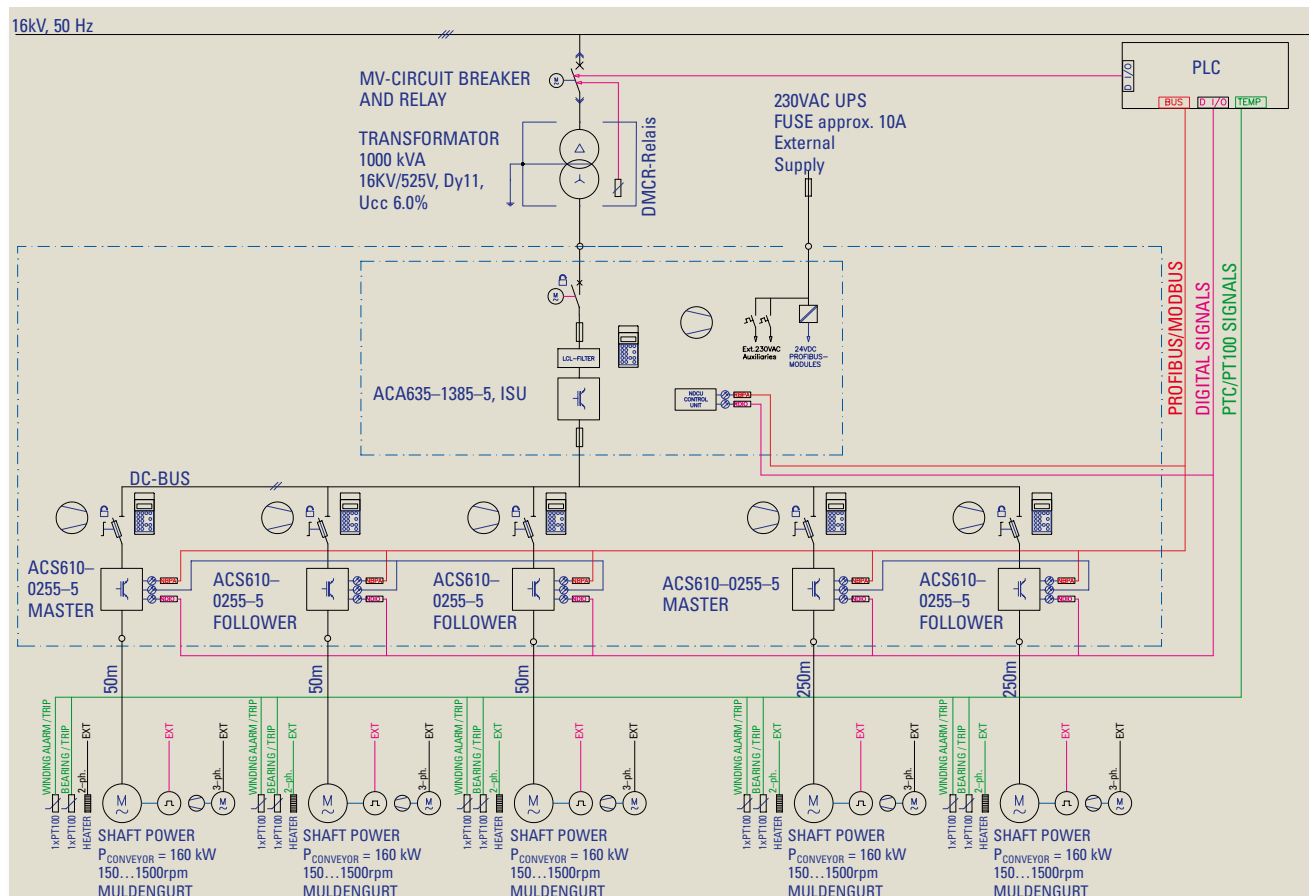

Figure 10: Single line diagram of the multidrive for downhill conveyors at Ciments Vigier, Switzerland
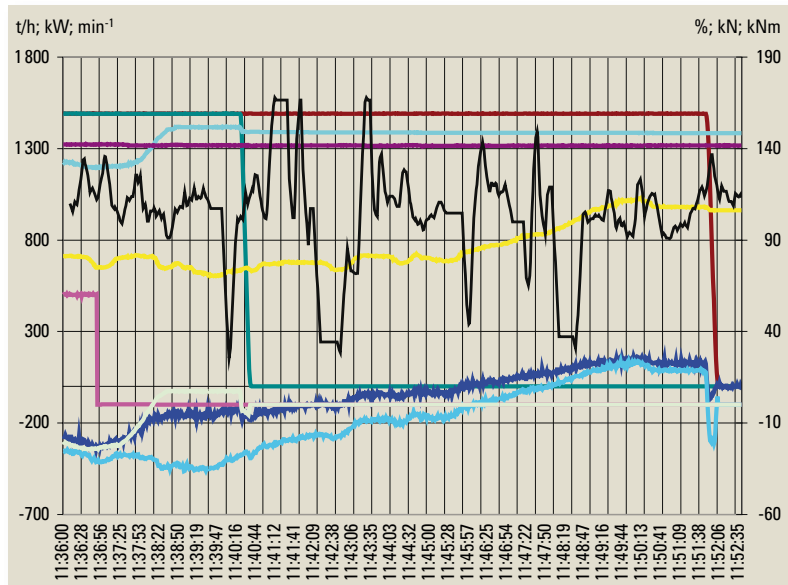
Figure 11: Emptying and stopping belts

❭ Fig. 12 shows the procedure for starting the belts when they are loaded with material:

❭ downhill belt 2 is started first and accelerated with an S-shaped curve to the nominal speed in 21 s
❭ after a certain time, downhill belt 1 is started and accelerated with an S-shaped curve to the nominal speed in 18 s

The belt tension of downhill belt 2 moves immediately into the negative range, which means that the loaded belt is being held back and is accelerated by its own load., The belt tension reduces when the belt has been accelerated with the predefined S-shaped ramp, as explained above. Finally, when the drive reaches its nominal speed the belt tension increases and comes to its operating point after a few oscillations. Downhill belt 1 shows a similar behaviour pattern. The crusher can only be started up when both belts are successfully in operation.

10 Safety protection

10.1 Emergency braking
For downhill conveyors the same protection philosophy has to be implemented as for cable cars or other down or uphill transport equipment. When it is in operation a loaded downhill regenerative conveyor must be restrained from running away by the power source. Any interruption of power or mechanical failure of the drive can cause the belt and load to run out of control. A brake that operates correctly is needed to prevent this. Practically all conveyors involving changes in level need, in addition to the braking force which can be provided by the drive itself, a mechanical brake for situations when the drive is not able to brake and to provide a holding action after the conveyor has come to a standstill.

For any downhill conveyor there is an obvious need to apply a controlled torque to decelerate the load at a reasonable rate. A very high torque would stress the belt too much and slipping could occur between the braking belt cylinder and the belt. When the resistance between the cylinder and the belt decreases and the belt starts to slip it becomes hazardous and it is almost impossible to stop the belt. That is why it is so important to apply a controlled torque with the drive in normal braking mode for about 20 seconds, or else with the brake for about 20 seconds. Belt slip can be detected by making two speed measurements and comparing them. One speed measurement is carried out on the driven motor or driven cylinder and the other measurement on an idler roll from the conveyor system or a speed pick-up directly on the belt. If belt slip is detected then the braking action has to be released immediately until the speeds at the two measuring points are synchronized; this is followed by renewed braking with controlled braking torque. Another important point is that the brake must be dimensioned to provide sufficient holding power to keep the conveyor belt securely at a standstill when it is fully loaded but out of operation.

10.2 Braking torque control with a mechanical brake
The pure motor braking is relatively simple because the braking torque has a direct relationship to the motor (generator) current. Direct control of the torque can be achieved by controlling the current. A mechanical brake for braking in emergency situations needs some additional mechanical adjustable devices in order to apply the correct braking torque. This is achieved by the incorporation of load cells. These cells measure the braking torque, and supply the correct braking information to the disc brake via the hydraulic system. Based on this information the braking torque can be applied appropriately without stressing the belt.

10.3 Belt control and protection strategy
The belt conveyor system requires a control system. The control system architecture is composed of the drive controller and the belt control system. The drive controller provides the speed and torque for starting, operating and stopping.
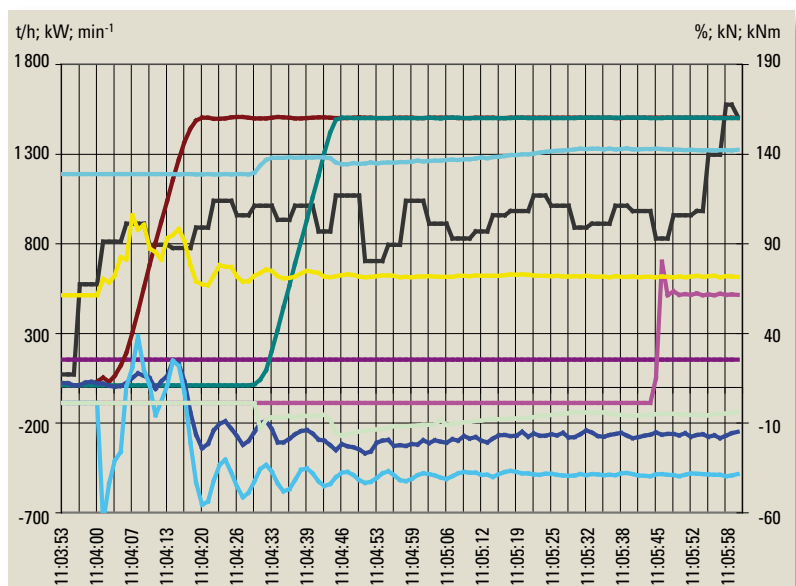

Figure 12: Starting with loaded belts

The belt control system provides run and stop commands, interlocks with other equipment and protection facilities for belt alignment, e.g. drift switches, belt slip, take-up over-travel, pull cord switches and, possibly, hopper level information. The belt control system consists of a number of belt permissives, operator stations, start warning systems, interlocks and sequencing of individual conveyors, as well as starting, interlocking and stopping procedures for the sequenced conveyors. The material flow has to be started by first starting the last conveyor downstream, but for stopping or interlocking it is necessary that the conveyor that is furthest upstream stops first.

10.4 Protection strategy

The high potential energy stored in the volume of material lying on the downhill conveyor has to be safely under control in all situations. The high standard of category 4 is required for personnel and equipment safety. The pull-rope switches are designed for optimum safe operation under severe conditions and are actuated by a plastic coated steel wire rope placed alongside the conveyor. The rope can be pulled at any point and it will trip, automatically lock the switches and activate the safe emergency stop circuit of the drive or the mechanical brake. Each switch is bi-directional in operation and has two ropes fitted to it from opposite directions terminating with a spring at the anchor points. The springs will operate the switch in the event of rope breakage. The rope length in both directions may be up to 50 m. After it has been tripped the mechanical latch can only be released at the switch itself by using the reset lever. The housings for the pull-rope and drift switches have to be correctly selected for normal, salty, dusty, coal or aggressive atmosphere to suit the site conditions.

The large numbers of pull-rope and drift switches are collected in groups from both sides of a remote I/O-box, which is placed in a distance of approximately 1 000 m. There are two possible ways of wiring the pull-rope switches to the safety circuit of the system. Each rope switch is hard-wired either to a category 4 safety relay, as is the case at Vigier, or to a serial bus communication system connected to safe remote digital inputs. For long distances the signals are converted via an optical link module and transmitted via optical cables to the PLC. Each pull-rope switch and drift switch has a second contact with its own address, so that the exact position can be indicated in the PLC, a remote station or a portable service PC. These signals are also collected the same way as mentioned above, but they are not integrated into the safety circuit.

11 Final remarks

It is a relatively simple matter to decide which capital investment to select when only the direct investment costs are considered, without environmental conditions or maintenance and life cycle costs. However, this paper has shown that the operating costs should, on an equal basis with environmental sustainability, play a far more important role in such a decision. A much broader approach to the decision-making process is called for. The possibility of grouping individual drives in an installation such as the multidrive at Ciments Vigier opens up new areas of application in which variable speed drives can be employed to increase the cost-efficiency over the lifecycle of a cement plant. The use of the AFE technology not only meets the requirement for efficient energy feedback to the network but is also well below the tolerance level in IEEE 519 with respect to the creation of current harmonics. ◀

List of abbreviations

4-Q	4-Quadrant drive: drive is able to accelerate and brake the load in both directions of rotation
LV-, MV- and HV-Equipment	Low voltage up to 1 000 V, medium voltage and high voltage > 1 000 V
MV-breaker	Medium voltage breaker. Isolates the medium voltage network from the load.
DOL-Motors	Direct on line motors which are connected direct to the network voltage of mainly 50 or 60 Hz and therefore can only be operated in fix speed.
AC-Network or AC-Supply	AC → Network or supply with alternating current, mainly 50 or 60 Hz.
DC-Link, DC-Bus or DC-Circuit	DC → Direct current. The DC-Intermediate circuit of frequency converters is the section after the rectifier which creates the DC-voltage.
IGBT	IGBT → Insulated gate bi-polar transistor. Power semiconductor of the newest generation, replacing mainly thyristors, GTO's, etc. in frequency converter drives.
THD	THD → Total harmonic distortions. Sum of harmonics (current THDI and voltage THD_U), created by the switching of power.
EMC	EMC → Electro magnetic compatibility
E-House	Electrical room where the electrical equipment is installed
VVVF	VVVF → Frequency converter drive with variable voltage and variable frequency
AFE	AFE → Active front end. A frequency converter drive with an IGBT instead of for example a diode rectifier.
IGBT-Modulation	With this semiconductor of the latest generation, it was possible to increase the switching frequency up to 12 kHz and even higher. The voltage source frequency converters are normally working with pulse width modulation to emulate a sinusoidal wave for the motor.