Regenerative Drives in the Megawatt Range for High-Performance Downhill Belt Conveyors

Jose Rodríguez, Jorge Pontt, Norbert Becker, and Alejandro Weinstein

***Abstract*—Downhill transport of ore from the mine to the beneficiation plant by means of belt conveyors introduces important advantages both for the personnel and for the equipment. Furthermore, if the conveyor is equipped with a regenerative ac drive, the system will generate an important amount of electrical energy for use in the process. This paper discusses the technical alternatives and the criteria used to select a solution, using modern converter–inverter drives in the megawatt and medium-voltage range. The considered drive alternatives are: 1) an ac wound-rotor induction motor drive with additional resistors; 2) an ac synchronous motor with cycloconverter; 3) an ac induction motor with current-source inverter; and 4) an induction motor with multilevel voltage-source inverter. The study reveals that, considering the main technical criteria, the use of a three-level active front end feeding a voltage-source three-level inverter is the most appropriate alternative.**

***Index Terms*—AC motor drives, conveyors, induction motor drives, mining industry.**

I. Introduction

ORE MINING continues to follow the trend toward higher locations. Today, altitudes of 3000 and 4000 m above sea level are by no means unusual for new copper mines [1], [2]. This places very heavy stress on personnel. Furthermore, the equipment must be designed for operation at high altitudes, which means the introduction of important derating.

It is, therefore, recommended to install at high altitude only that equipment directly required for mining the ore. Further processing in lower lying regions yields a number of advantages for the plant operator and for the equipment.

A very attractive solution to this problem is the use of downhill belt conveyors, which transport the mineral from the mine to the concentrator. Important advantages of this solution are: 1) personnel have less stress due to the high altitude and 2) the equipment does not need to be highly derated.

The bidirectional nature of the power flow of electrical machines permits the transformation of the potential energy of the ore in the conveyor into electrical energy that can be regenerated to the electrical supply of the mine, generating important energy savings.

When the amount of ore to be handled is in the range of 100 000 tons/day, the power generated by the conveyor may exceed several megawatts and must be delivered to the electrical utility. Medium-voltage drives must be considered in this power range.

At this voltage level, different converter topologies must be evaluated: cycloconverters, current-source inverters (CSIs) [3], three-level voltage-source inverters (VSIs) [4], and cascaded multilevel (CML) inverters [5].

This paper presents a technical comparison of the different medium-voltage drive alternatives for high-power regenerative conveyors focused on the special conditions existing at the Los Pelambres copper mine in Chile. The paper includes: 1) general requirements for conveyor drives; 2) special requirements for downhill conveyor drives; and 3) how the different solutions satisfy the requirements, with their advantages and disadvantages.

II. Requirements of Drives for Conveyors

A. General Requirements

The most important requirements in belt conveyor systems are as follows:

1) high availability, to permit a continuous operation of the process;
2) high reliability, to avoid unprogrammed interruptions of the production;
3) smooth control of torque to minimize the belt tension transients during acceleration and deceleration and also in extreme situations; smooth torque also reduces the wear of the rotating parts of the belt;
4) good controller to assure the load sharing and to provide the starting and braking ramp;
5) drive system for the electrical motors of the conveyors must be robust with respect to perturbations in the electrical source;
6) possibility of belt speed variation in response to load variation (this capability generates energy savings);
7) good interaction with the power supply: reduced input current harmonics and high power factor; this aspect is especially valid in mining distribution systems and considering the increasing importance of power quality issues;
8) field experience.

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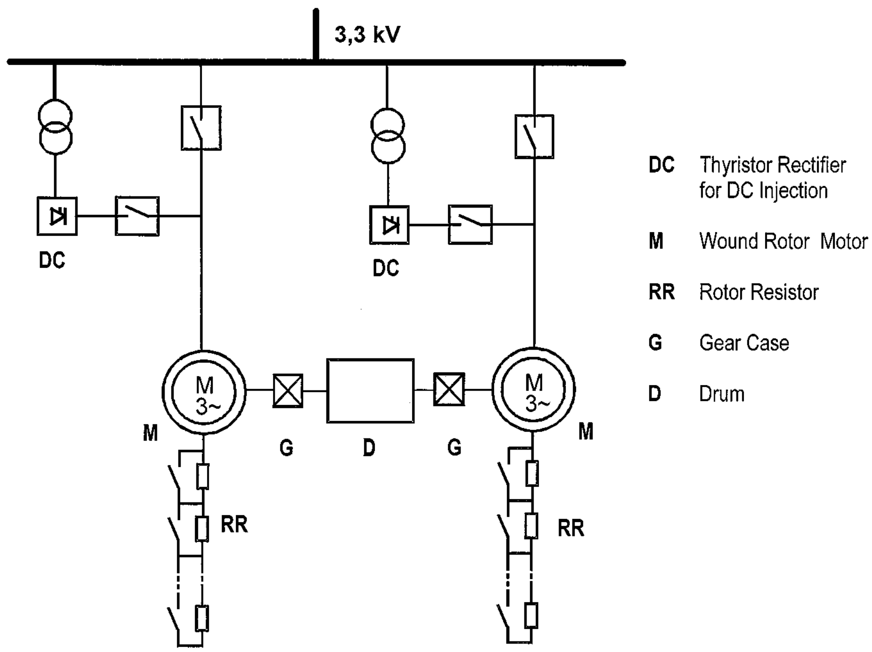

Fig. 1. Wound-rotor induction motor drive.

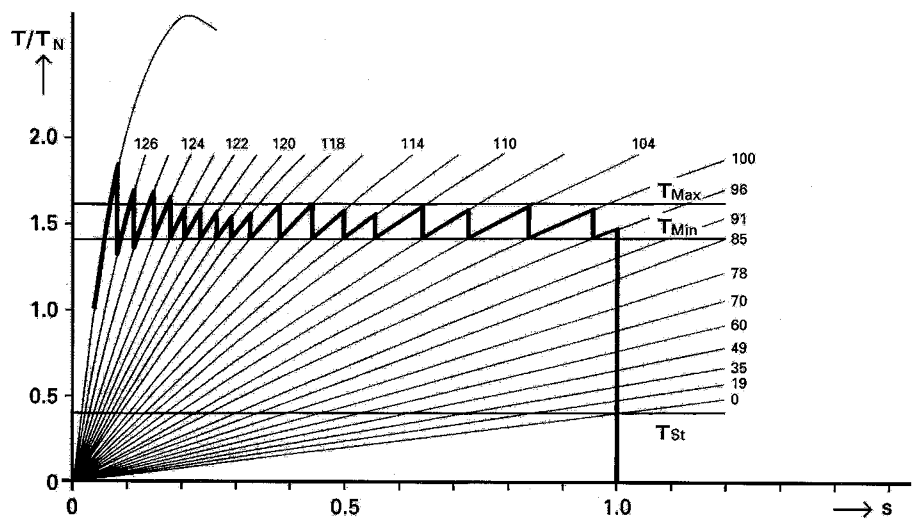

Fig. 2. Torque–speed characteristic of a wound-rotor induction motor drive.

B. Special Requirements in Downhill Conveyors

1) The drive system must be able to generate a continuous braking torque.
2) The drive system must be able to transmit the energy of the load back to the three-phase source. It must have regeneration capability.
3) A controlled breaking of the belt must be guaranteed in case of loss of the electric grid.

All these requirements are considered as the comparison criteria.

C. Power of the Drive

At the Los Pelambres copper mine, the conveyor delivers approximately 2.5 MW to each electrical machine. Due to the power range of the application, only medium-voltage (3.3 kV) motors and converters are considered.

III. Drive Alternatives

A. Wound-Rotor Induction Motor Drive

Fig. 1 presents two wound-rotor induction motor drives, which use additional resistors in the rotor to change the torque–speed characteristics, as shown in Fig. 2 [6]. This solution has been widely used in conveyor drive applications and, for this reason, there exists an extensive amount of knowledge concerning this alternative. The simplicity of this system, especially of the power components, originates a robust operation with high availability and low cost.

In this solution, a thyristor rectifier is used for dc current injection to brake the conveyor. As can be observed in Fig. 2, this alternative produces big stepwise changes in the torque, which increase the wear on the mechanical parts: bearings, drums, belt. The control strategy of the motor does not permit the operation

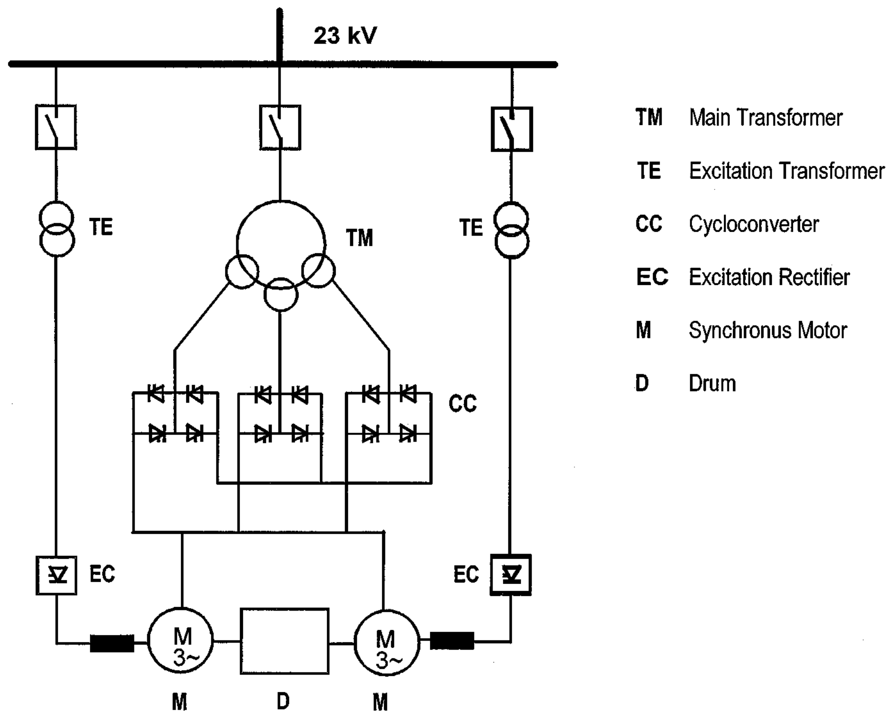

Fig. 3. Synchronous motors with cycloconverters.

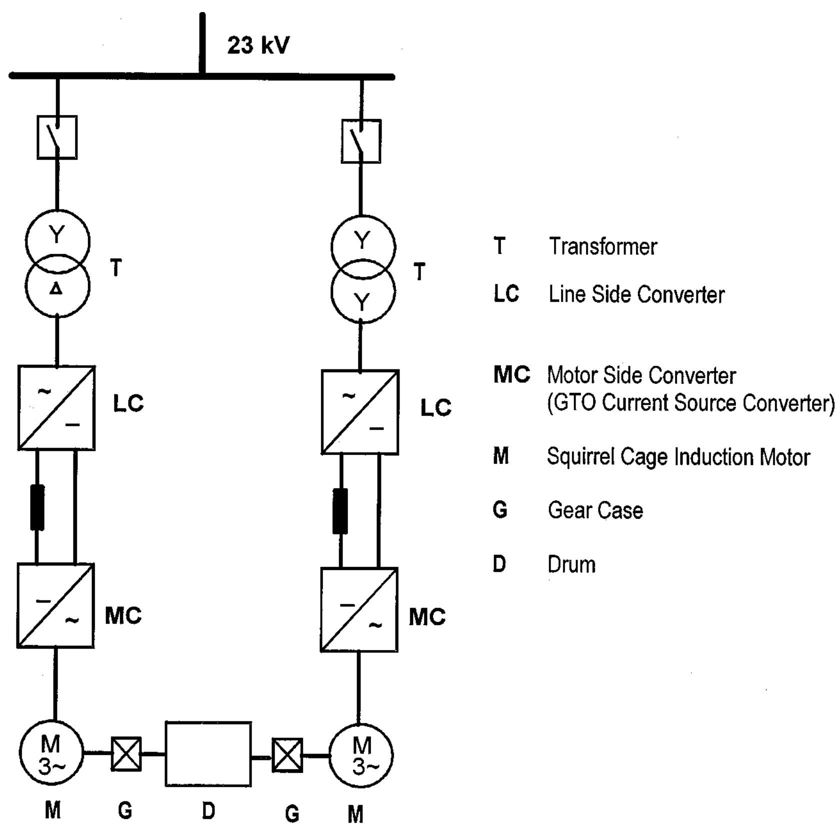

Fig. 4. Induction motors with PWM-CSI inverters.

of the belt at variable speeds. In addition, there is torqueless free time during the transition from normal operation to dc-braking operation. The braking torque is only effective from rated speed down to 30% of rated speed.

B. Synchronous Motor With Cycloconverter

In this alternative, the necessary drive power is provided by two cycloconverter-fed three-phase synchronous motors, as shown in Fig. 3. The low speed of this configuration allows

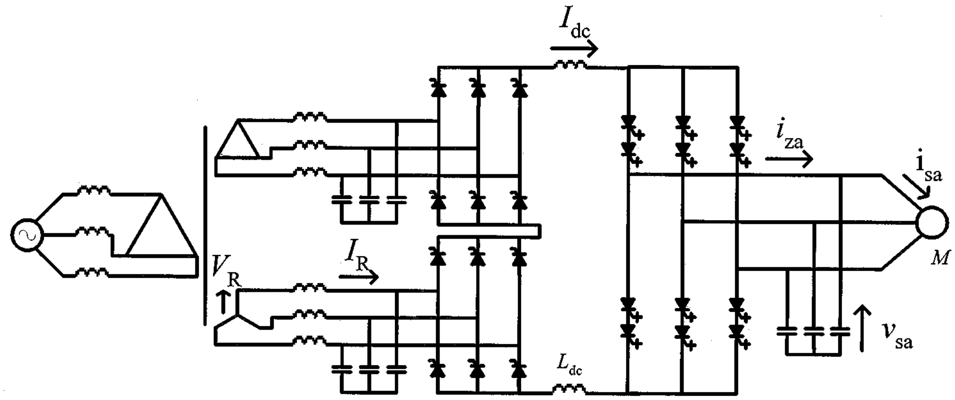

Fig. 5. Power circuit of the PWM-CSI inverter.

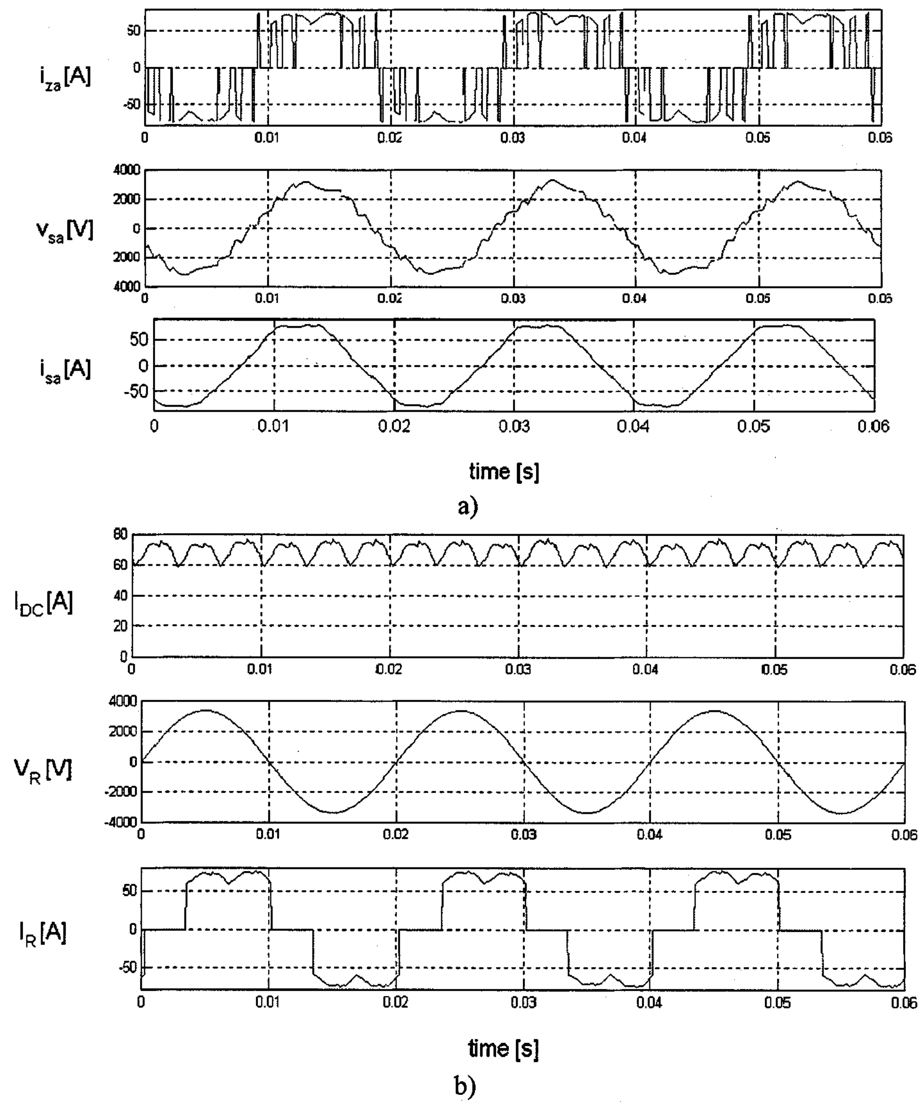

Fig. 6. Waveforms of the PWM-CSI inverter. Current and voltages at (a) motor side and (b) input side.

the direct coupling to the drum, avoiding the use of gears. This solution provides a smooth torque control by using vector control strategy and variable-speed operation for the conveyor [7]. The cycloconverter generates an important amount of reactive power at the input and injects current harmonics to the source. One drawback is that the cycloconverter cannot operate in case of line loss.

C. *Induction Motor With CSI*

This solution, shown in Fig. 4, considers squirrel-cage induction motors fed by a pulsewidth modulation CSI (PWM-CSI) inverter with gate-turn-off thyristors (GTOs). The current in the dc link is controlled by a line-commutated rectifier. The PWM-CSI inverter needs a capacitive filter at the output, shown in Fig. 5, to avoid overvoltages in the motor.

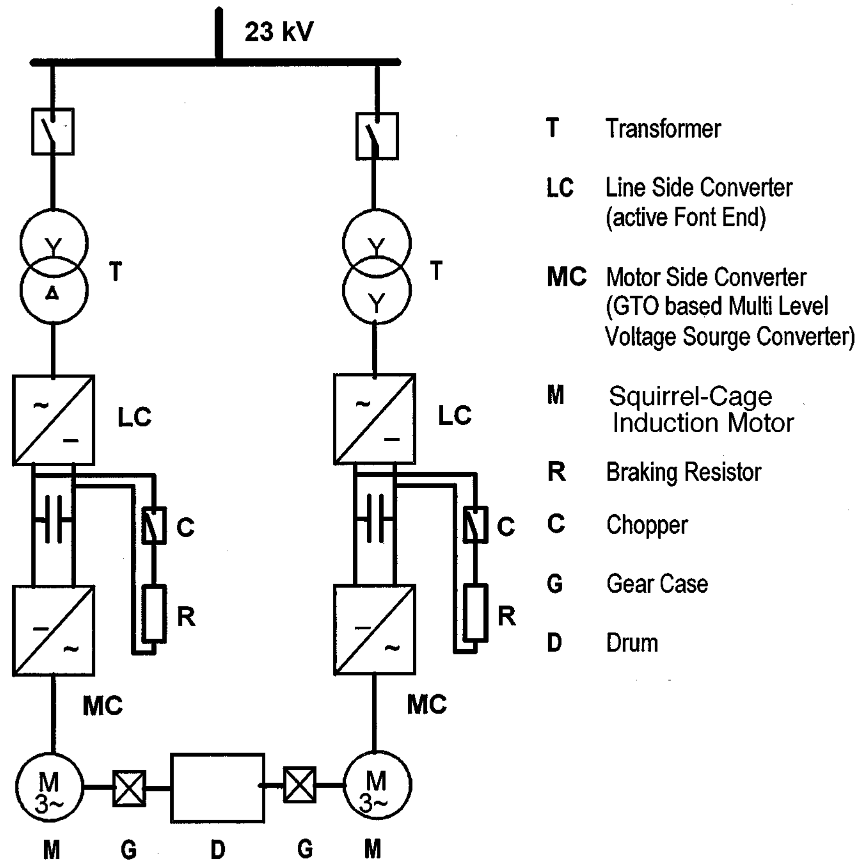

Fig. 7. Induction motor with three-level VSI.

As can be observed in Fig. 6, the voltage and current delivered by this inverter to the motor have a very low distortion. This inverter can work very easily in the regenerative mode. This is achieved by reversing the polarity of the dc-link voltage, because the dc-link current I_{DC} cannot reverse its direction due to the presence of the thyristors. To reach this condition, the input rectifier must operate in the inverting mode, with a firing angle $\alpha > 90°$.

It is very important to note that, in the inverting mode, the line-commutated rectifier is especially prone to commutation failures that can be originated by reductions (sags) in the line voltage [8]. Since in this application the drives will be operating permanently in the inverting mode, this aspect has a negative impact on the reliability of the system. In addition, this solution does not allow the use of the energy stored in the dc link when there is a loss of the power supply. The use of a controlled line-commutated rectifier at the input side generates current harmonics and reactive power.

As can be observed in Fig. 6(b), the input current i_R has the typical waveform of a six-pulse rectifier with fifth and seventh harmonics. These harmonics are eliminated by the 12-pulse configuration used in Fig. 5.

A solution to these problems has been proposed in [9], where a PWM GTO current-source rectifier (CSR) is used at the front end. This new alternative has been recently proposed as a medium-voltage drive with sinusoidal input and output waveforms for conveyor applications [10].

D. Induction Motor With VSI

Another interesting possibility considers the use of three-level VSIs with GTOs to feed the induction motors, as shown in Fig. 7. To work in the regenerative mode, dual converters should be used at the input side, because the polarity of the dc-link voltage cannot be reversed due to the presence of the electrolytic capacitors and the flywheel diodes of the inverter. Fig. 8 shows a 12-pulse dual converter for a three-level inverter. To allow regeneration of power, the dc-link current I_{DC} must be negative which is achieved by operating rectifiers RI-B and RII-B permanently in the inverting mode. As explained in the case of CSI drives, this operation mode for the rectifiers is prone to commutation failures. It is well known that inverter drives fed by dual converters suffer from frequent fuse blowing when they have regenerative operation. This can be solved by the use of a three-level active front end (AFE) as shown in Fig. 9. An AFE is an inverter working as a controlled PWM rectifier with the following advantages:

1) fully regenerative;
2) extremely low current harmonics injection;
3) adjustable input power factor;
4) less affected by variations in the line voltage.

This solution permits controlled electrical braking during loss of the line, through the use of dc choppers connected to the dc link as shown in Fig. 7. In effect, during the loss of the power

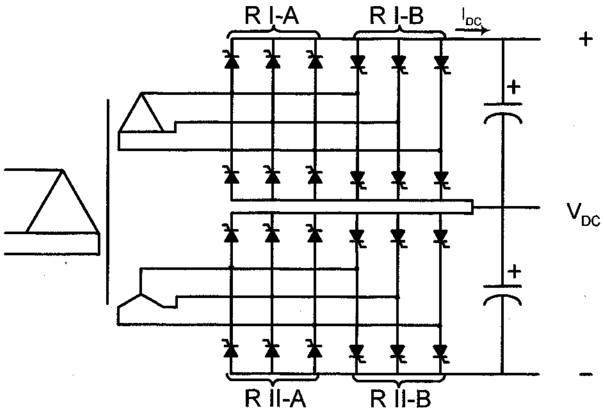

Fig. 8. Line-side dual converter for a three-level inverter.

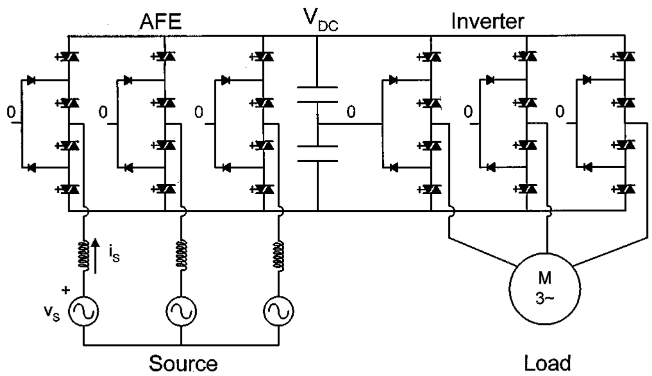

Fig. 9. Power circuit of GTOs three-level AFE–inverter.

supply of the mine, the input AFE can be disabled very easily and the energy fed back by the induction motor is dissipated in the braking resistor controlled by the chopper, increasing the reliability of the drive. This solution has the best technical characteristics.

Fig. 10 presents the phase voltage delivered by the three-level inverter to the motor, which has a more sinusoidal waveform in comparison to a simple two-level inverter with step-up transformer.

Fig. 11 shows the behavior of the frequency converter of Fig. 9 when the drive goes from the motoring to the generating mode. The dc-link voltage V_{DC} has a small increase, while the control system reverses the current, producing an operation with power factor -1. It must be noticed that the input current of the AFE has a reduced distortion.

The use of an AFE increases the number of GTOs in the power circuit and, consequently, increases the cost.

A very attractive solution for medium-voltage drives, from the motor point of view, is the CML inverter, shown in Fig. 12 [11]. This inverter uses several series-connected low-voltage cells to generate a load voltage with reduced distortion. As can be observed in Fig. 13, each cell has a noncontrolled three-phase diode rectifier at the line side, which does not permit the reversing of power flow. For this reason, this topology cannot be considered for this application, unless a regenerative cell is used.

Finally, Table I summarizes the selected alternatives with their respective advantages and disadvantages.

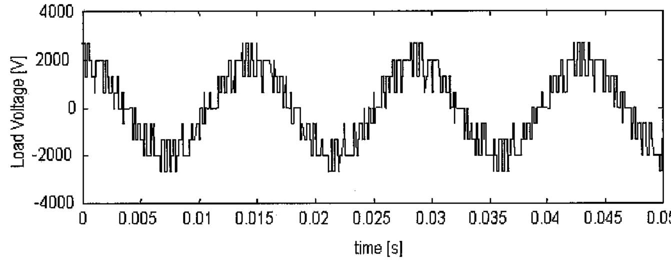

Fig. 10. Motor phase voltage delivered by a three-level inverter.

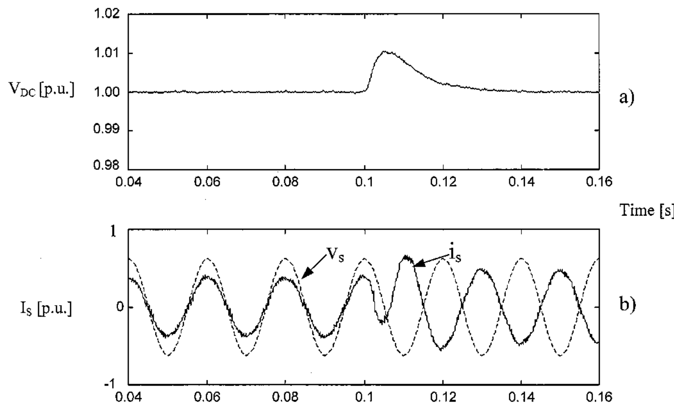

Fig. 11. AFE in the regeneration mode. (a) DC-link voltage V_{DC} (p.u.). (b) Input current i_S (p.u.).

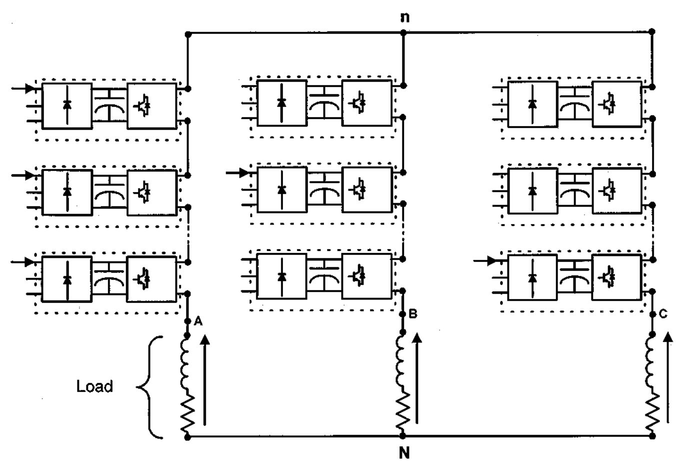

Fig. 12. CML inverter.

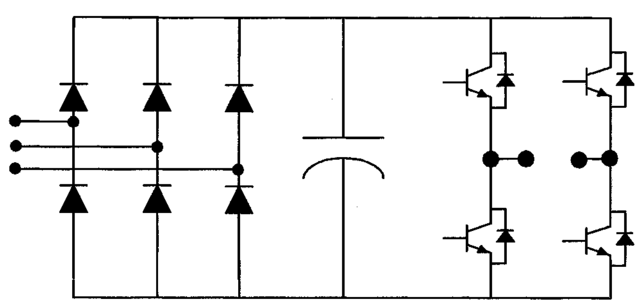

Fig. 13. Cell of a CML inverter.

TABLE I
COMPARISON OF THE DIFFERENT ALTERNATIVES

ALTERNATIVE	ADVANTAGES	DISADVANTAGES
Wound Rotor Induction Motor Drive	• Know-How • Robust • Low cost • High availability	• Wear on the mechanical parts: bearings, drums, belt, etc. • No belt speed adjustment • Torqueless free time between the transition from normal operation to DC-braking operation • Braking torque is only effective from rated speed down to 30% of the rated velocity
Synchronous Motor with Cycloconverter	• No gear case • Energy savings by matching belt speed to material flow • Reduced wear on the brakes	• Reactive power demand • Harmonics • No regeneration feedback in case of line loss
Induction Motor with CSI	• Squirrel cage induction motor • Energy savings by matching belt speed to material flow • Reduced wear on the breakes	• No regeneration feedback in case of line loss • Reactive power demand • Harmonics • Prone to commutation failure
VSI with a dual Converter at the input	• Squirre cage induction motor • Braking torque is effective from rated speed down to standstill • Energy savings by matching belt speed to material flow	• Prone to commutation failure • Reactive power demand • Harmonics
Induction Motor with Multilevel VSI and AFE	• Energy fed back to a pulsed resistor in case of line loss • Squirre cage induction motor • Braking torque is effective from rated speed down to standstill • Energy savings by matching belt speed to material flow • Robust to variations of line voltage	• Complex line side Converter

IV. COMMENTS AND CONCLUSIONS

This paper has reviewed different medium-voltage drive alternatives for downhill conveyors in the megawatt range. Due to the high power and permanent regenerative condition, special restrictions were considered. Each drive must be capable of delivering the conveyor energy back to the electrical supply.

In this type of application, reliability is by far the most relevant criteria to select the most appropriate alternative. With this consideration, line-commutated rectifiers working in the inverting mode are prone to commutation failures and, for this reason, they hardly satisfy the previously mentioned criteria.

From a technical point of view, the use of three-level VSIs fed by an AFE is the best alternative. This alternative was finally selected and used in the project. The conveyors are now in operation and permanently regenerating a total power of 15 MW.

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