Novel 20-MW Downhill Conveyor System Using Three-Level Converters

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***Abstract*—This paper presents a very new drive system used to transport ore from the mine down to the concentrator plant in the copper mine "Los Pelambres" . Eight 2500-kW motors are driven by three-level inverters with gate-turn-off thyristors (GTOs). A three-level active front end is used at the input side of each inverter. A GTO chopper is used to provide controlled electrical braking in case of line loss. The paper presents the requirements and alternatives for the drive system and the control strategies for the converters and the belt. A novel application of the selective harmonic elimination method is used to reduce the input current harmonics. Special attention is dedicated to the interaction with the electrical network. The most relevant features of the system are: 1) fuseless operation; 2) adjustable power factor; 3) reduced input current harmonics; 4) smooth transition between motoring and regenerating modes; and 5) 15 MW of regenerated power with more than six months of successful operation.**

***Index Terms*—Active front end, conveyor drives, high-power drives, three-level inverters.**

I. Introduction

THE copper mine "Los Pelambres" is located in the Los Andes mountain range in Chile at 3400 m of altitude [1]. This high altitude places additional stress on equipment and personnel. In addition, avalanches endanger the site location. Thus, the location of the concentrator at a lower altitude is mandatory. A downhill tunnel conveyor has been selected as the most suitable transport alternative for the ore produced by the mine.

The bidirectional nature of the power flow in electrical machinery 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 energy savings. This is a major issue because the conveyor will transport 5800 ton/h in the initial phase, generating several megawatts of electrical power.

Traditionally, in the megawatt range, the electric drive used in downhill conveyors is the wound-rotor induction motor with additional resistors in the rotor.

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For the first time, at Los Pelambres three-level active front end (AFE) and three-level inverters with a total installed power of 20 MW have been used, which constitutes a breakthrough in the mining industry and in conveyor technology. The following sections include the requirements for the drive systems, the drive alternatives, the power converters of the selected drive, and the control strategy for the converters and for the belt. Special attention is dedicated to the interaction of the AFE with the network. Finally, some important operational results of the drive system are given.

II. Description of the Conveyor System

The belt conveyor transporting system is composed of three individual conveyors with lengths of 5905, 5281, and 1467 m. The average inclination is 11% and, at some places, even 24%. The mine is located at 1700-m altitude. In the initial phase of the project, the belt will transport 5800 ton/h. The rated strength of the belt is 7800 N/mm. Two drive pulleys are used for each belt conveyor and each single drive has a power of 2500 kW.

III. Requirements and Alternatives for the Drives

A. Requirements

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

- high availability;
- smooth torque control;
- controlled starting and braking ramp;
- possibility of belt-speed variation;
- high power factor;
- reduced input current harmonics;
- robust regarding perturbations from the network.

Downhill conveyors have the following extra requirements:

- capability to generate a continuous braking torque;
- capability to transmit the energy of the load back to the electrical grid;
- smooth transition from motoring to generating operation.

B. Drive Alternatives

The following drive alternatives were studied for this project [3]:

1) wound-rotor induction motor drive with additional rotor resistors;
2) ac synchronous motor with cycloconverters;

TABLE I
COMPARISON OF THE DIFFERENT DRIVE ALTERNATIVES

Alternative	Advantages	Disadvantages
Wound Rotor Induction Motor Drive	-Know-How -Robust -High availability	-Wear-out 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 PWM - CSI	-Energy savings by matching belt speed to material flow -Reduced wear on the brakes	-No regeneration feedback in case of line loss -Reactive power demand -Harmonics -In case of line loss the fuses will blow during regenerative operation
Induction Motor with Multilevel VSI and AFE	-Energy fed back to a pulsed resistor in case of line loss -Braking torque is effective from rated speed down to still stand -Energy savings by matching belt speed to material flow -Robust to variations of line voltage	-Complex line side Converter

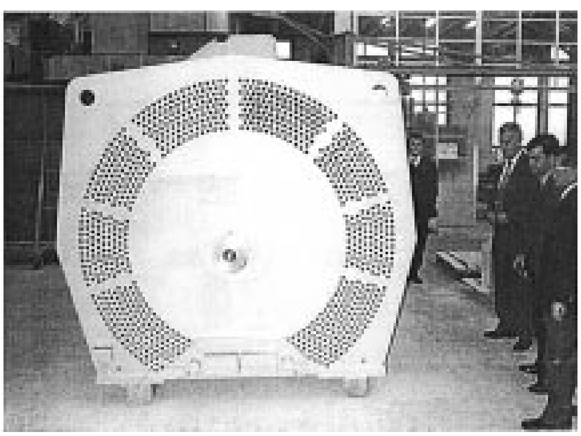

Fig. 1. 2500-kW conveyor motor.

3) squirrel-cage induction motor with pulsewidth-modulated current-source inverter (PWM-CSI);
4) squirrel-cage induction motor with three-level voltage source inverter and three-level AFE at the line side.

Table I summarizes the technical advantages and disadvantages of the different drive systems available for regenerative operation at high power levels. All drives using power converters provide smooth torque control and for this reason they experience a reduced wearout of the mechanical parts. In addition, these drives allow belt speed reduction improving the efficiency. Alternative 4) is more robust to variations in the line voltage, a typical feature in mine distribution systems, increasing the reliability of the belt. Moreover, the use of a voltage source inverter allows for electrical braking in case of line loss by using a pulsed resistor in the dc link. A detailed analysis of the different drive alternatives can be found in [3].

TABLE II
MOTOR CHARACTERISTICS

Power: 2,500 Kw	Power factor: 0.87
Voltage: 3,000 V	Efficiency: 0.96
Frequency: 50 Hz	Inertia: 360 Kgm^{-1}
Speed: 995 rpm	Weight: 16 Ton.

IV. Description of the Drive

A. Motors

The squirrel-cage induction motors have IP55 protection and are equipped with a welded all-steel housing and integrated tubular cooler. A total of 902 cooling tubes made of stainless steel were installed in the stator housing, as observed in Fig. 1. Special considerations were taken into account with the site altitude. The most relevant characteristics of the motors are summarized in Table II. Each motor is equipped with: 1) an anticondensation heating system; 2) temperature monitoring

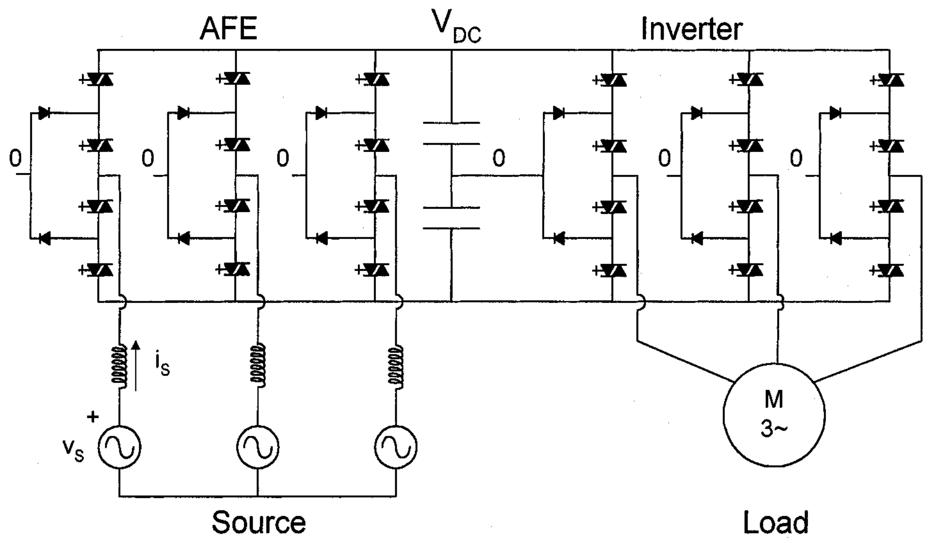

Fig. 2. Power circuit of the three-level inverter–AFE system.

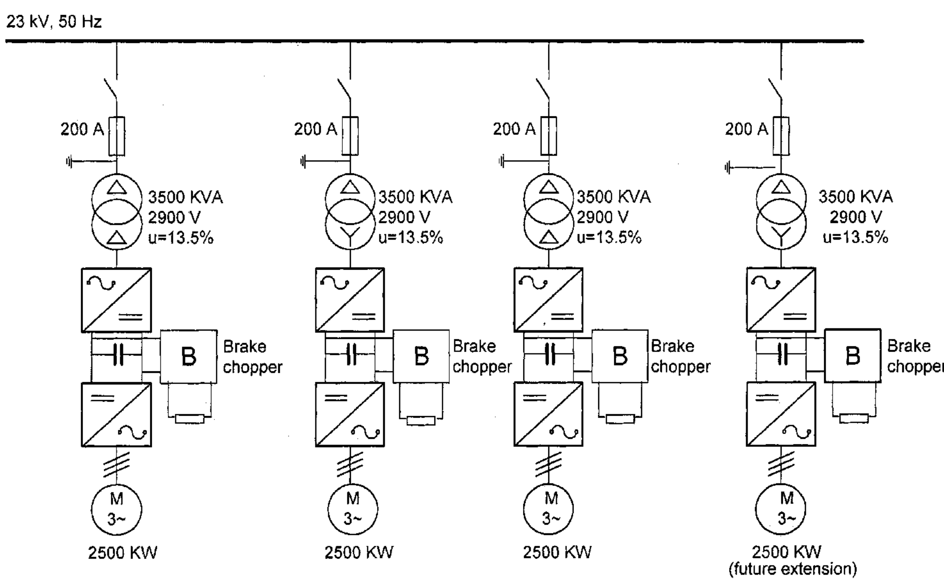

Fig. 3. Drive station with four motors (final extension).

for the winding and the bearings; 3) redundant digital speed measurements; and 4) vibration monitoring for the bearings.

B. Converters

Fig. 2 presents the simplified power circuit of the three-level inverter with three-level AFE rated 3440 kVA and 3000 V, used to control each induction motor. Some relevant features of the converter system are fuseless design of inverter and AFE and identical design of the GTO phase modules on the motor and line sides.

The belt delivers energy to the inverter through the induction motor, which works most of the time as a generator. The energy in the dc link is fed back to the three-phase system by the AFE. In the extreme situation of a blackout, it is not possible to deliver energy back to the three-phase source. For this reason, two GTO choppers are connected in parallel to the dc-link capacitors to allow controlled electrical breaking in case of line loss.

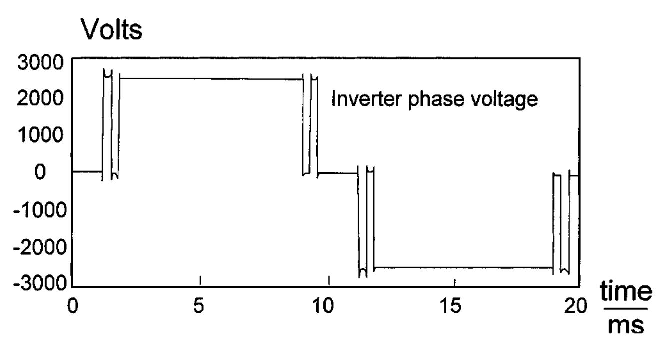

Fig. 4. Phase voltage of a single AFE.

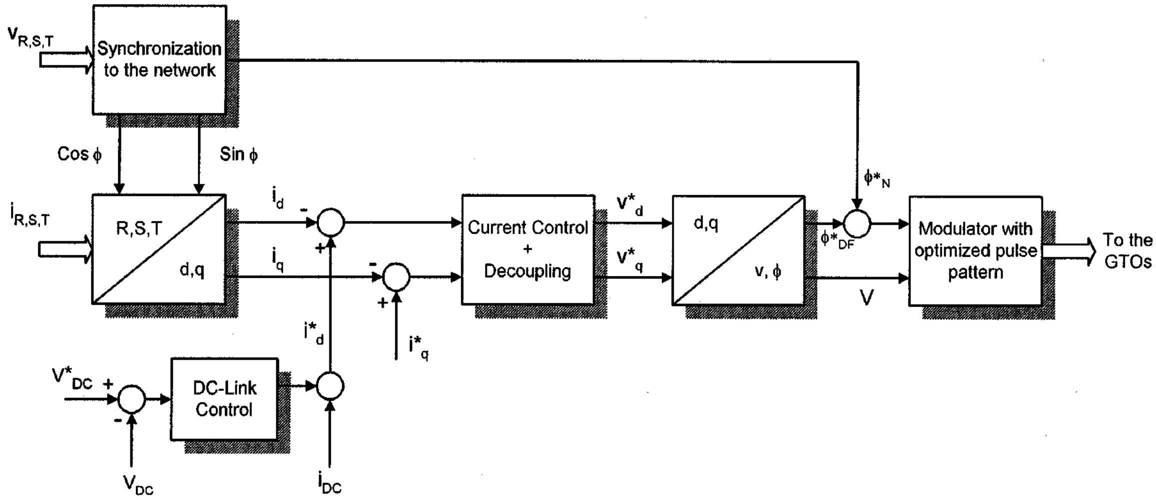

Fig. 5. Simplified structure of the AFE control.

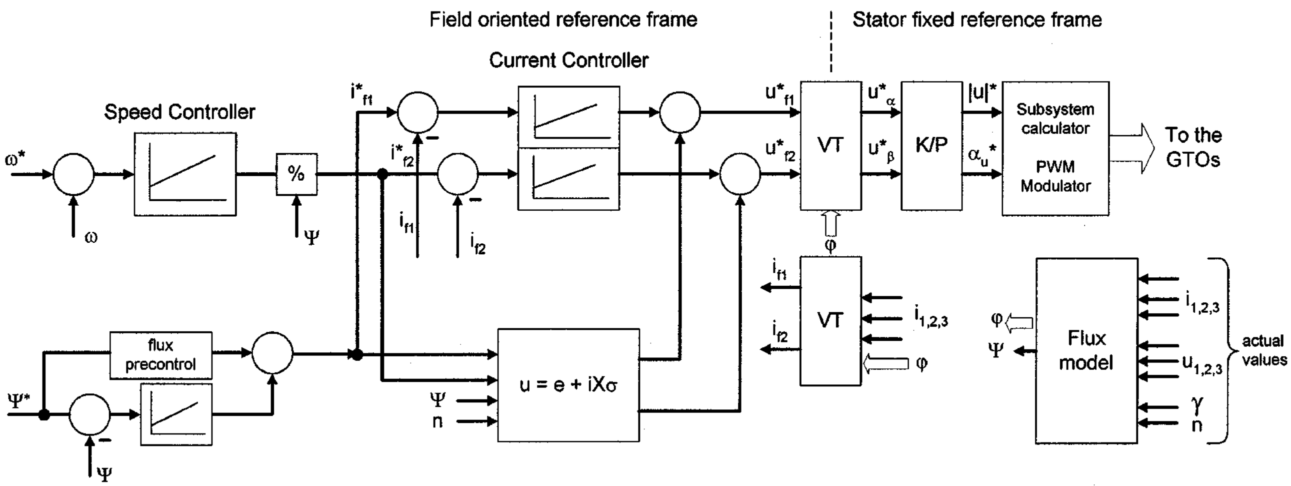

Fig. 6. Control of the inverter and the machine.

C. One Drive Station

Fig. 3 presents the single-line diagram for a drive station, which is supplied with a 23- kV cable ring. Two motors are used to drive one drum and the third one drives a second drum. A fourth drive is considered for future expansion. The input transformers of the drive are rated 3 500 kVA and 2900 V with delta–delta and delta–wye connection to achieve a 12-pulse configuration, thus improving the total quality of input current.

Every drive station has its own switch station container to house the 23-kV high-voltage system, the uninterruptible power supply (UPS), and the batteries. Power inverters, AFE, choppers, drive controls, and auxiliary equipment for two 2500-kW drives are housed in another drive unit container.

V. Control Strategy

A. Control of the AFE

The use of GTOs in the power circuit of the AFE and the inverter limits the switching frequency to approximately 350 Hz. For this reason, an optimized modulation strategy with reduced number of commutations is used for the AFEs.

First, each pair of drives is fed by a transformer secondary with 30° phase displacement to reach a 12-pulse configuration, which reduces the 5-, 7-, 17-, and 19th-order current harmonics. The selective harmonic elimination method is used to eliminate harmonics 11th and 13th, which can be achieved introducing three commutations each at 90° to the input voltage of the AFE. Fig. 4 shows the input voltage of the AFE with three switching angles and 90° symmetry. Each capacitor in the dc link has a voltage of 2500 V. With this modulation strategy, the lowest input harmonics generated by two drives are the 23rd and 25th. The input currents of the converter (i_R, i_S, i_T) are expressed in a rotating frame of reference obtaining current i_d proportional to the active power and current iq proportional to the reactive power. The separated control of these currents, as shown in Fig. 5, allows a continuos control of the power factor at the input AFE.

The block diagram of Fig. 5 is done with one signal processor. The reference value of the active current (i_d^*) is obtained from the dc-link voltage controller and the dc-link current precontrol.

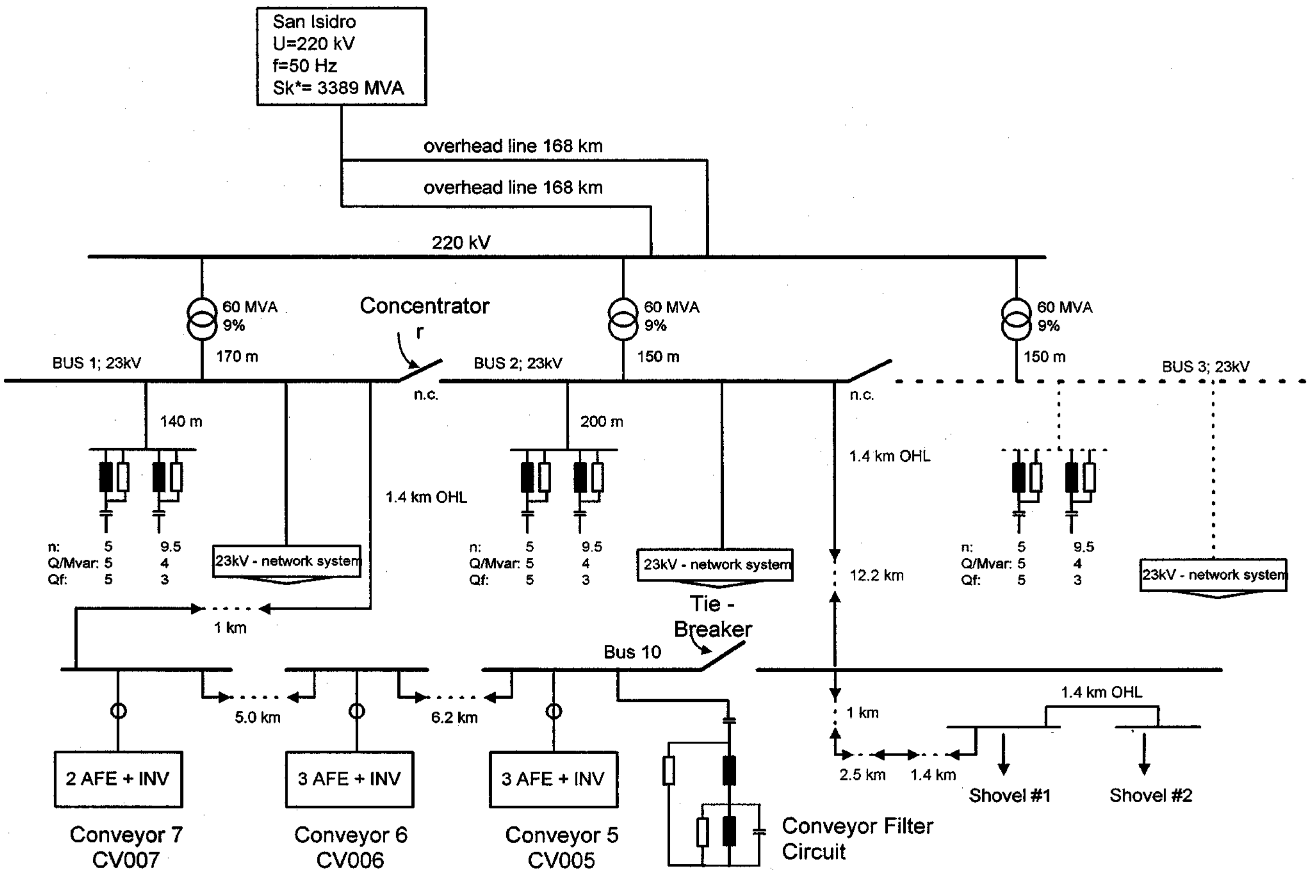

Fig. 7. Simplified single-line diagram for harmonics study.

B. Control of the Three-Level Inverter

An optimized space-vector modulation is used to control the three-level inverter. The field-oriented control method, also called vector control, is used to achieve high-quality speed and torque control of the induction machine. Fig. 6 shows the structure of the speed control system.

The flux of the machine ψ is calculated by using two models. One model for higher speeds is based on voltages and currents in the stator. A second model was used for lower speeds based on stator currents and rotor position. The stator currents are transformed in a rotating frame of reference oriented with the flux, originating a current proportional to the torque (i_{f2}) and another current proportional to the flux (i_{f1}). Precontrol loops are used to improve the performance of the control system. A more detailed description of the control of the AFE and inverter can be found in [5].

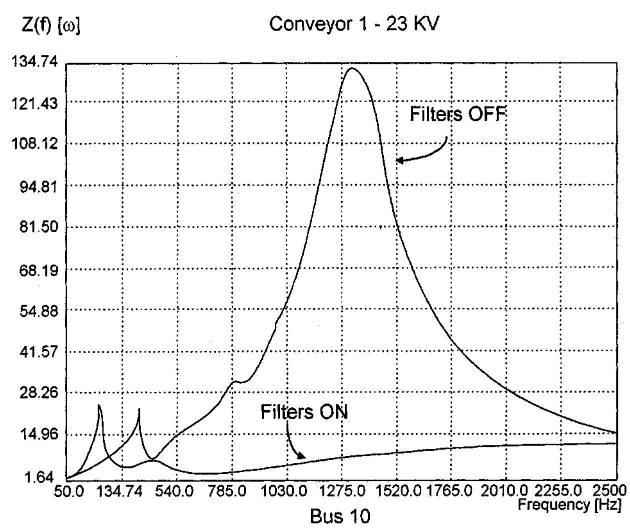

Fig. 8. Behavior of the impedance $Z(f)$ of bus 10, 23 kV with tie breaker open.

C. Control of the Chopper

In case of a blackout (line loss), the drive loses its capability to regenerate power to the three-phase network. To allow electrical braking, a chopper is connected in parallel with each capacitor in the dc link. The energy fed back by the inverter is dissipated in the braking resistor controlled by the chopper.

The instance of network power failure is detected by the inverter, initiating the following steps: 1) when the dc-link voltage reaches the upper threshold, the chopper switches ON and OFF, regulating the voltage V_{DC} automatically to a constant value; 2) the AFE is blocked; and 3) the regenerated energy is dissipated in the braking resistor until the belt is stopped.

D. Control and Monitoring of the Belt

Each drive unit has its own digital controller which is commanded by a programmable logic controller (PLC) located in

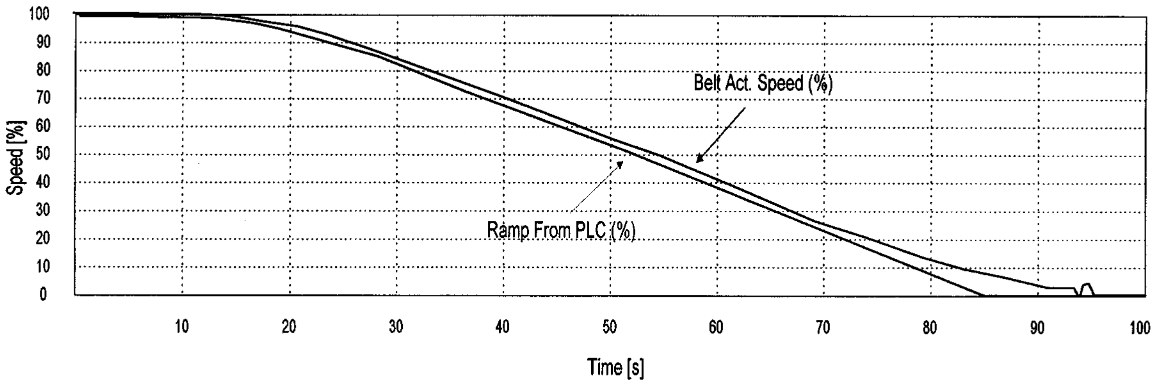

Fig. 9. Measured braking curve of the belt.

the conveyor station. Redundant PLCs are used to increase the reliability. The following variables are monitored to identify irregularities and failures: belt tension, slip of the belt (especially important during startup and braking), overspeed, bearing temperature, vibration monitoring, belt damage, mechanical brake monitoring, etc. After a start/stop command is received from the PLC, the reference value is transmitted to an s-ramp function generator which provides a smooth speed reference to the drives. The stopping of the belt is by far the most critical maneuver in the operation of the conveyor.

VI. Network Interaction

The AFE is the converter family with the smallest input current harmonics. However, due to the high power of the equipment and the characteristics of a mining distribution system, the interaction with the electrical network is of particular importance. Fig. 7 presents the single-line diagram suitable to study the influence of the conveyors in the harmonics of the system. The mine is fed from the main substation San Isidro with two overhead lines of 168 km. The main substation has a voltage of 220 kV with a short-circuit power of 3389 MVA. Two main transformers of 60 MVA each reduce the voltage from 220 to 23 kV. The drawings with dashed lines represent the future expansion. The concentrator has two grinding lines operating in parallel and each line has a semi-autogenous grinding (SAG) mill with two ball mills. The SAG mill is driven by one synchronous motor of 18 000 hp fed by a cycloconverter.

A complete harmonic analysis of the Los Pelambres electrical system was carried out at the basic engineering stage of the project. The aim of the study was to have a well-designed system to assure reliability and power quality of the system concerning:

1) reactive power compensation (power factor);
2) voltage regulation;
3) meeting harmonic limits given in IEEE-519-92 and in national regulations;
4) equipment specifications.

Each cycloconverter used for the SAG mills has, at the input side, a two-branch high-pass filter of a 9-Mvar total tuned to the harmonics 5 and 9.5.

For the sake of simplicity, only the behavior of conveyor 5 at busbar 10 of 23 kV will be discussed. A simplified equivalent system of 99 elements, 49 busbars, and 25 harmonics sources were considered and simulated with the software Harmonix [4]. Fig. 8 shows the behavior of the impedance of bus 10, showing a strong resonance at a frequency of approximately 1300 Hz. At the 23rd (1150 Hz) and 25th (1250 Hz) harmonics, bus 10 has very large impedances of approximately 80 and 120 Ω, respectively. These harmonics are generated by the AFEs of the conveyors. This resonance is originated by the interaction between cable capacitance and network inductance and produces a high-voltage distortion at this point.

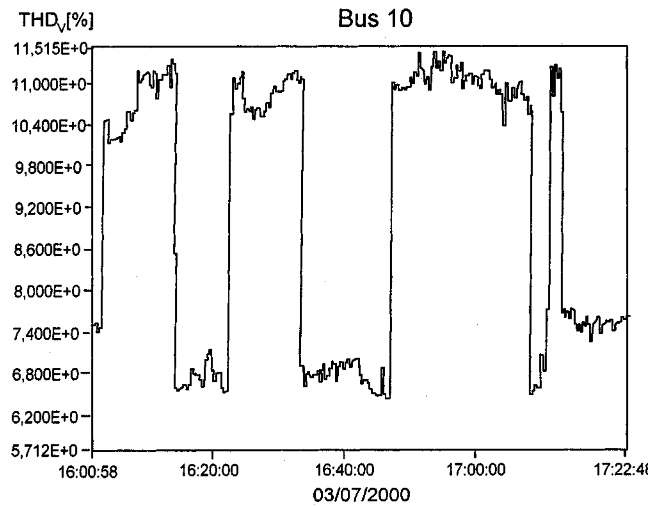

Fig. 10. Measured distortion (THD_v) of bus 10 without conveyor filter.

To keep the voltage harmonic level within the IEEE 519 limits, a filter of 9 Mvar with two branches tuned to the 5.5th and 12th harmonics was included. With this filter, the impedance of the bus at 1250 Hz is reduced to a value small enough to keep the voltage distortion within the allowed limit.

VII. Operational Results

The conveyor was successfully erected and commissioned and has delivered more than one year of satisfactory operation at rated conditions, transporting 5800 ton/h and generating a total power of 15 MW with power factor ≈ -1.

Fig. 9 presents the speed measured when the belt was stopped with electrical braking at a load of 5800 ton/h. The required

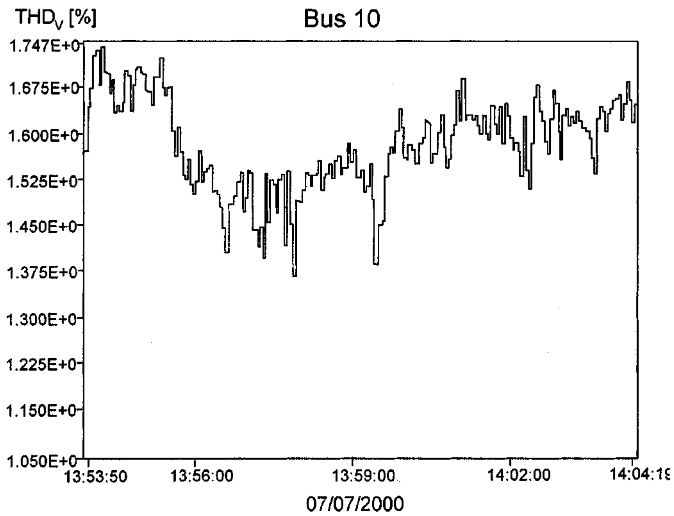

Fig. 11. Measured distortion (THD$_v$) of bus 10 with conveyor filter.

braking time was less than 100 s and the speed presents a very smooth profile.

Fig. 10 presents the total harmonic distortion for the voltage (THD$_v$) measured without filter for the conveyors with the tie breaker at bus 10 open. The contract established that the THD$_v$ should not exceed the limit of 5% under normal operating conditions. It can be observed in Fig. 10 that the THD$_v$ without filter is higher than the allowed value. In addition, starting the conveyor without its filter produces the trip of an undervoltage relay.

Fig. 11 shows the distortion of bus 10 when the conveyors filter is connected. The distortion is reduced to a value of THD$_v$ $= 1.74\%$, which is smaller than the limit of 5%. In addition, there are no disturbances during the starting phase of the conveyor when operating with the filter.

VIII. Comments and Conclusions

Key aspects related with the use of high power three-level inverter–AFE drive systems in regenerative conveyors have been presented in this paper. The solution presented in this project allows for the regeneration of energy from the belt to the electrical system.

The use of three-level inverters with vector control at the motor side produces a very precise torque control and smooth belt behavior.

The use of a three-level AFE permits the regeneration of energy and very smooth transition from motoring to regenerative operation with adjustable power factor.

An unexpected resonance originated by the cable capacitance produces a high distortion at the input of the conveyor. The problem was solved by using a high-pass filter.

The technological solution adopted in this project has been applied for the very first time in high-power downhill conveyor systems, establishing a new state-of-the-art technology in this field.

References

[1] E. Cereceda, "Production of Los Pelambres starts in 3 months" (in Spanish), *Minería Chilena*, no. 217, pp. 7–15, July 1999.

[2] W. Dittrich and O. Einenkel, "Downhill tunnel conveyor on the Chilean side of the Andes," *Braunkohle, Surf. Mining*, vol. 52, no. 3, pp. 235–244, May/June 2000.

[3] J. Rodríguez, J. Pontt, N. Becker, and A. Weinstein, "Regenerative drives in the megawatt range for high performance downhill belt conveyors," *IEEE Trans. Ind. Applicat.*, vol. 38, pp. 203–210, Jan./Feb. 2002.

[4] J. Pontt, E. Perelli, and C. Pontt, "Harmonix: A software package for teaching harmonics in power systems," in *Proc. 7th Eur. Conf. Power Electronics and Applications, EPE'97*, Trondheim, Norway, Sept. 1997, pp. 4.996–4.1001.

[5] T. Salzmann, G. Kratz, and C. Däubler, "High-power drive system with advanced power ciruitry and improved digital control," *IEEE Trans. Ind. Applicat.*, vol. 29, pp. 168–174, Jan./Feb. 1993.

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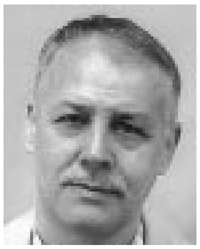

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