Resonances in a High-Power Active-Front-End Rectifier System

José R. Rodríguez, *Senior Member, IEEE*, Jorge Pontt, *Senior Member, IEEE*, Rodrigo Huerta, Gerardo Alzamora, Norbert Becker, Samir Kouro, *Student Member, IEEE*, Patricio Cortés, *Student Member, IEEE*, and Pablo Lezana

***Abstract*—This paper presents the application of high-power three-level active-front-end rectifiers to regenerate energy in a downhill conveyor system. The selective harmonic elimination method is used to eliminate harmonics 11 and 13, working with very low switching frequency, where six-pulse harmonic orders $6k \pm 1$ are eliminated by the delta–wye connection of the transformer. In this way, the input current at the mains is highly sinusoidal with small harmonics starting at frequencies of order 23 and 25. Resonances have been detected, originated mainly by the capacitances of feeding cables and noneliminated harmonics, which produce high-voltage distortion. Theoretical and field measurements present the problem and the solution by using a specially designed high-pass power filter.**

***Index Terms*—Active rectifiers, conveyors, pulsewidth modulation (PWM), selective harmonic elimination (SHE).**

I. Introduction

THE *Los Pelambres* copper mine is located in Los Andes mountain range at 3400 m altitude [1]. This high altitude places additional stresses on equipment and personnel. In addition, avalanches endanger the site location. Thus, the location of the concentrator in a lower altitude is mandatory.

Taking advantage of the altitude difference between the mine and the concentrator, a downhill tunnel conveyor belt was selected as the most suitable transport alternative for the ore produced by the mine.

The conveyor belt transporting system is composed of three individual conveyors with lengths of 5905, 5281, and 1467 m. The average inclination is 11% and at some locations even 24%.

The conveyors transport about 5800 t/h, allowing electrical regeneration in the order of several megawatts. The selected drives for this project must allow four-quadrant operation in order to deliver the generated power by the belts to the grid. In addition, the final solution has eight motors of 2500 kW each, giving a total installed power of 20 000 kW.

Among several alternatives, three-level inverters fed by the well-known technology of active-front-end (AFE) three-level rectifiers [6], [11] were selected due to following main advantages [3]:

- fully regenerative;
- extremely low current harmonics injection;
- adjustable input power factor;
- less affected by variations in the line voltage.

All these characteristics allow for a broad range of power conversion systems [1]–[5], [13], [14]. Switching losses and network interaction limit the operation of three-level AFE high-power converters, especially using gate-turn-off thyristor (GTO) semiconductors [6]. That is why low switching frequency and reduced harmonic distortion are the main goals by using optimum pattern pulsewidth modulation (PWM) with a kind of selective harmonic elimination modulation (SHEPWM). In addition, overvoltages, common-mode voltage issues, and electromagnetic interference (EMI) caused by PWM commutations may also be reduced [7]–[12].

This paper presents a deeper description of the power system of the mine, the power circuit of the drive, the modulation, and a study of the interaction between AFE converters and the grid. Simulation studies reveal the presence of a resonance that is avoided with the use of a power filter. Finally, experimental results obtained in the field are included.

II. Description of the System

Fig. 1 shows a reduced single-line diagram of the electrical system used in the *Los Pelambres* mine, including conveyors 5, 6, and 7 (CV005, CV006, and CV007). Conveyors 5 and 6 have three AFE–inverter units, while conveyor 7 has only two. Buses 8, 9, and 10 are connected using cables of lengths 2.4, 5, and 6.2 km, respectively. The concentrator uses ball mills and large semiautogenous (SAG) mills driven by synchronous motors fed by cycloconverters. Each cycloconverter used for the SAG mills has at the input side a two-branch high-pass filter of 9 Mvar total tuned to harmonics 5 and 9.5 to improve the resulting harmonic response of the line. Choosing the 5th and 9th harmonics allows for reducing the total characteristic response of the line due to the long cables with its parasitic capacitances and the cable inductance [9], [10]. Power filters to compensate harmonics and

Manuscript received December 29, 2003; revised February 20, 2004. Abstract published on the Internet January 13, 2005. This work was supported by the Chilean Research Council CONICYT under Project 1030368 and by the Research Direction of the Universidad Técnica Federico Santa María.

J. R. Rodríguez, J. Pontt, S. Kouro, P. Cortés, and P. Lezana are with the Departamento de Electrónica, Universidad Técnica Federico Santa Maria, Valparaíso, Chile (e-mail: jrp@elo.utfsm.cl).

R. Huerta was with the Departamento de Electrónica, Universidad Técnica Federico Santa Maria, Valparaíso, Chile. He is now with the ESO-Paranal Observatory, Antofagasta, Chile (e-mail: rach@elo.utfsm.cl).

G. Alzamora is with the Electrical Department, Compañía Minera Los Pelambres, Santiago, Chile (e-mail: galzam@vtr.net).

N. Becker is with Siemens AG Erlangen, D-91052 Erlangen, Germany (e-mail: norbert.becker@erl9.siemens.de).

Digital Object Identifier 10.1109/TIE.2005.843907

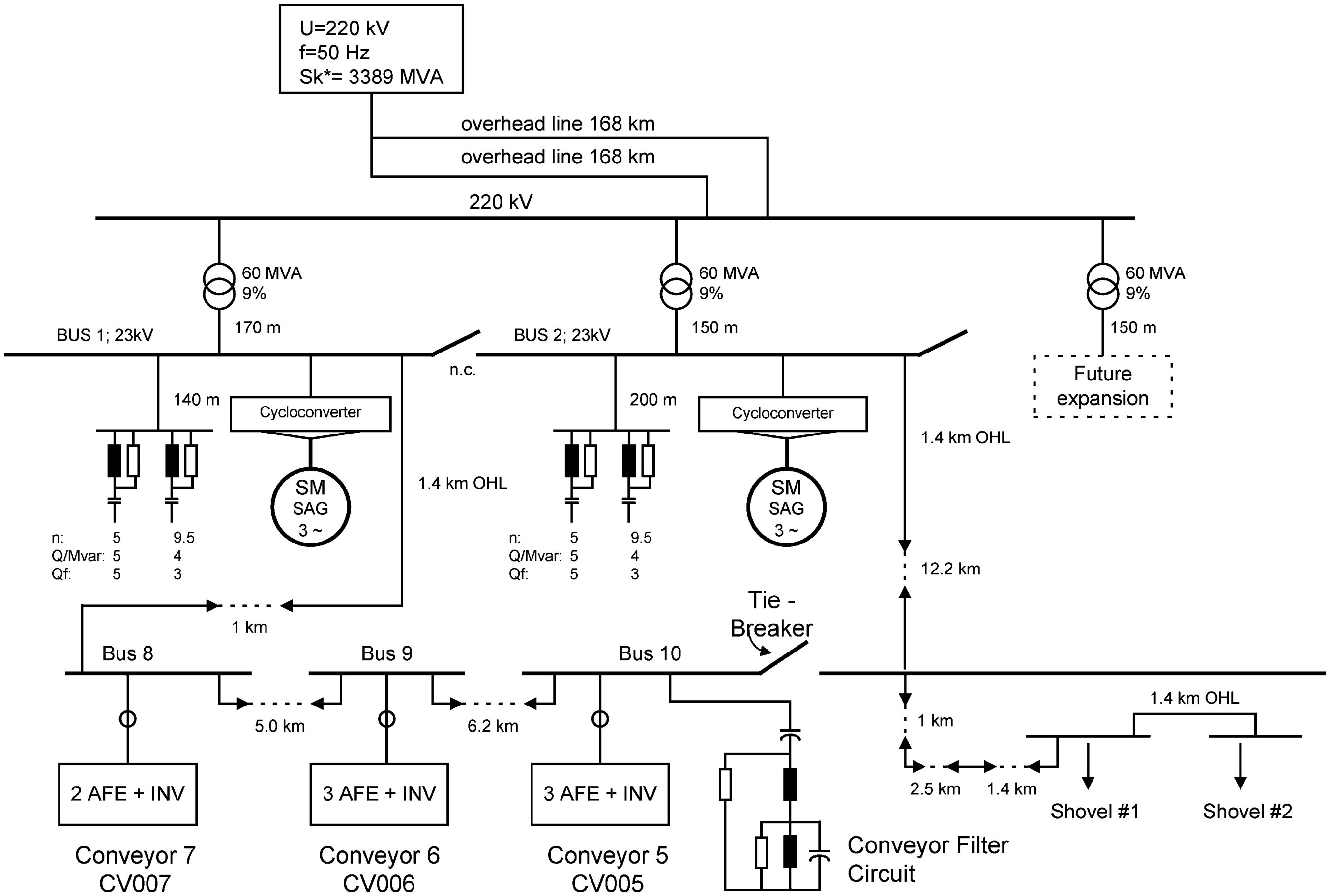

Fig. 1. Simplified single-line diagram of the electrical system at Los Pelambres.

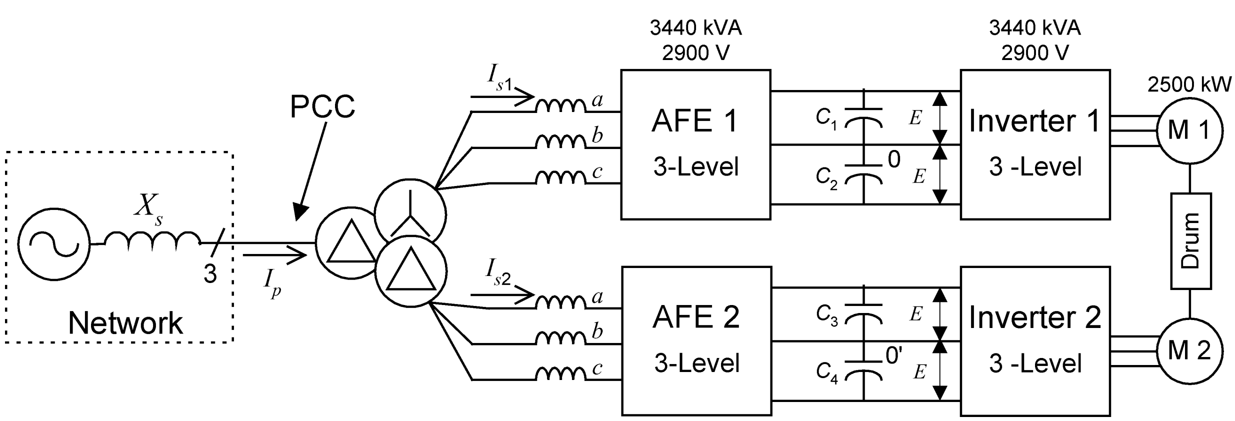

Fig. 2. Drive station with two motors.

the reactive power of each cycloconverter can also be seen in Fig. 1.

III. Description of the Drives

A. One Drive Station

Fig. 2 presents the simplified diagram for a drive station (for instance, CV007), which is supplied with a 23-kV cable (see Fig. 1). Two motors are used to drive one drum of the belt and a third unit drives a second drum in conveyors 6 and 7. A fourth drive is considered for a future expansion. The input transformers of the drive are rated 3500 kVA and 2900 V with delta–delta and delta–wye connection achieving a 12-pulse configuration, thus improving the total input current quality.

B. AFE–Inverter Units

Fig. 3 presents the simplified power circuit of the three-level inverter with three-level AFE rectifier rated 3440 kVA and 2900 V, used to control each induction motor. Some relevant features of the converter system are: fuseless design of the inverter and AFE, and identical design of the GTO phase legs on the motor and line sides.

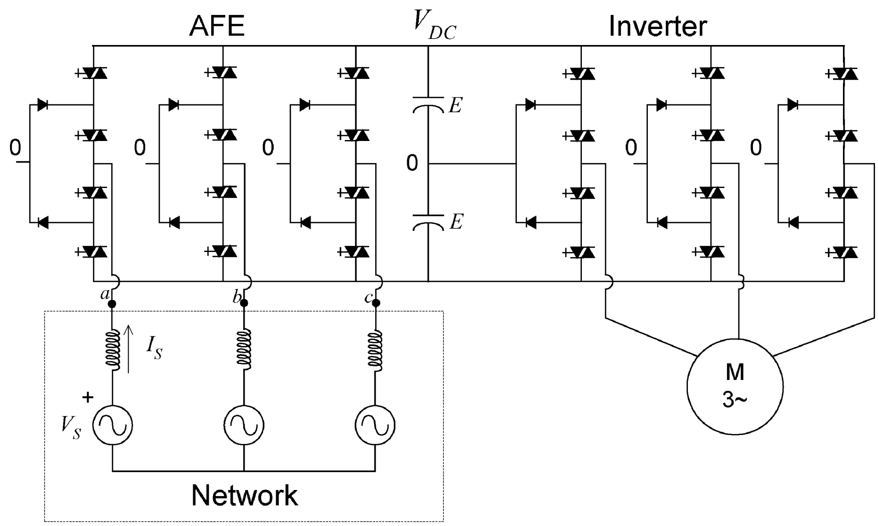

Fig. 3. Power circuit of the three-level inverter–AFE system.

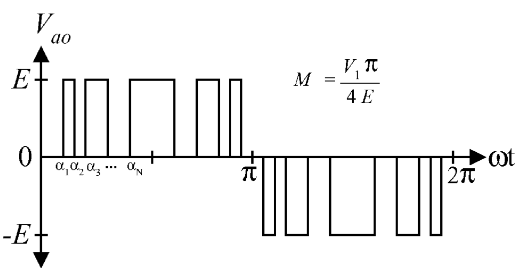

Fig. 4. SHE switching pattern with N angles.

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 ($V_{\rm DC}$) 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 for controlled electrical braking in case of line loss (not included in Fig. 3).

IV. Modulation Scheme for the AFE Rectifiers

Selective harmonic elimination (SHE) is the selected control strategy for the AFE rectifiers. Since the inverter and the AFE rectifier use GTOs, a commutation pattern working with low switching frequency is used to reduce switching losses. SHE offers the possibility to work with a reduced number of commutations.

A. SHE Fundamentals

SHE is based on the analysis of the Fourier series of the voltage generated by the converter [6]. Fig. 4 shows the waveform of the voltage between points "a" and "o" of Fig. 3 (V_{ao}), for the general case of N commutations every 90°.

Due to symmetry in the waveform shown in Fig. 4 the expansion in Fourier series may be reduced to

$$V_{ao} = \sum_{n=1,3,5,\ldots}^{\infty} V_n \cdot \sin(n\omega t) \quad (1)$$

with:

$$V_n = \frac{4E}{n\pi}\left[\sum_{k=1}^{N}(-1)^{k+1}\cos(n\alpha_k)\right] \quad (2)$$

where V_{ao} is the converter phase voltage, n is the harmonic number, V_n the amplitude of harmonic n, and E the half dc-link voltage. From (1), (2), and a proper numerical method [6], solutions to eliminate the desired harmonics can be obtained.

The 12-pulse configuration of the input transformer permits the elimination of all harmonics of order $6k \pm 1$, k odd. These are the well known harmonics 5, 7, 17, 19,….

The modulation scheme uses three commutation angles to eliminate the lowest harmonics, in this case 11 and 13. This is achieved through the following equations:

$$V_1 = \frac{4E}{\pi}[\cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3)] \quad (3)$$

$$V_{11} = \frac{4E}{11\cdot\pi}[\cos(11\cdot\alpha_1) - \cos(11\cdot\alpha_2) + \cos(11\cdot\alpha_3)] = 0 \quad (4)$$

$$V_{13} = \frac{4E}{13\cdot\pi}[\cos(13\cdot\alpha_1) - \cos(13\cdot\alpha_2) + \cos(13\cdot\alpha_3)] = 0 \quad (5)$$

with V_{11} and V_{13} both equal to zero. It must be noticed that (3) is used to control the amplitude of the fundamental voltage V_1.

With this strategy, the lowest harmonics in the primary side of the transformer have orders 23 and 25.

The fundamental component V_1 controlled by the modulation index (M) and dc-link voltage E is given by

$$V_1 = \frac{4}{\pi}\cdot E \cdot M. \quad (6)$$

Under this definition of modulation index, $M = 1$ means a block voltage operation and no elimination of harmonics at all. Fig. 5 shows the harmonics in voltage V_{ao} for different modulation indexes. It can be observed that in all operating points harmonics 11 and 13 are completely eliminated.

B. Noneliminated Harmonics

Fig. 6 shows the behavior of harmonics 23 and 25 measured at the AFE side between "a"–"o" points (Fig. 3) for different

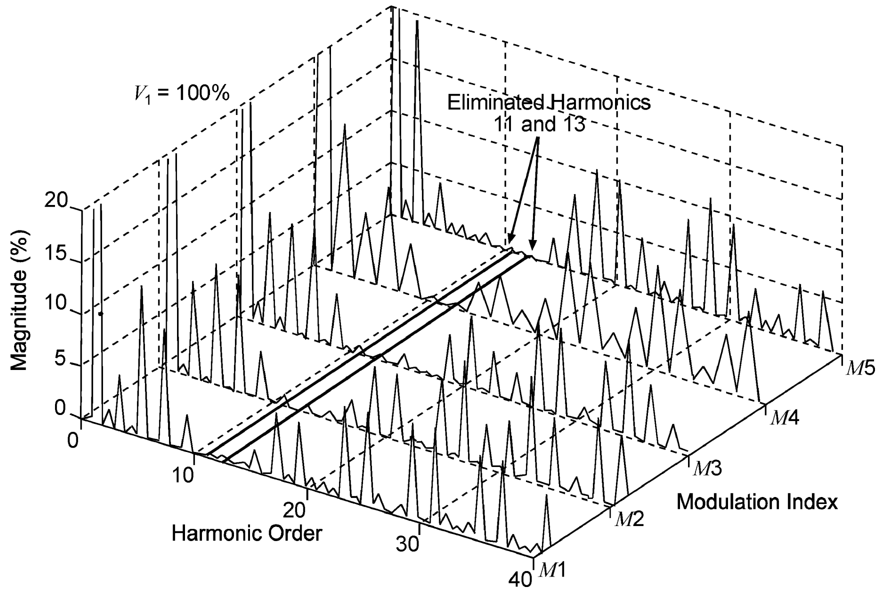

Fig. 5. Experimental spectrum for three-angle V_{ao} pattern for different modulation indexes with elimination of 11th- and 13th-order harmonic: $M1 = 0.872$, $M2 = 0.891$, $M3 = 0.897$, $M4 = 0.910$, and $M5 = 0.940$.

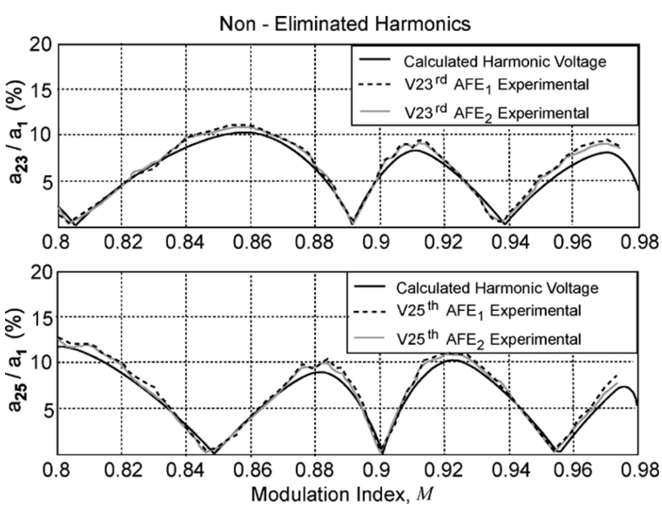

Fig. 6. Noneliminated harmonic pattern, calculated and experimental results: 23rd and 25th orders. Three-angle scheme.

modulation indexes. It can be seen that these voltage harmonics can reach amplitudes as high as 13% and they will be present in the input current.

V. 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.

A complete harmonic analysis of *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 and to assure reliability and power quality of the system concerning the following:

1) reactive power compensation (power factor);
2) voltage regulation;
3) meeting harmonic limits given in IEEE-519-92 [8] and Chilean regulations [7];
4) equipment specifications.

For the analysis, a simplified equivalent system of 99 elements, 49 bus bars, and 25 harmonics sources was considered and simulated with the software Harmonix [4].

An interesting phenomenon occurred at bus bar 10, which is related to the use of long cables to feed the conveyors. Fig. 7 presents the simplified electrical circuit used to feed one AFE rectifier, including the transformer (R_t, L_t), network impedances (R_n, L_n), and the model of the cables. The cable model includes parasitic capacitors which originate a strong resonance in the impedance of bus bars 8, 9, and 10 centered at a frequency of 1300 Hz. Fig. 8 presents the resonance phenomena at bus bar 10 with rated voltage of 23 kV. It can be observed that the resonance frequency of this bus bar is very near to harmonics 23rd (1150 Hz) and 25th (1250 Hz) injected by the AFE rectifier, originating a high distortion in the voltage.

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 designed and included. The structure of the harmonic filter was chosen as a double-tuned filter scheme in order to minimize the total volume, due to the reduced available room space. The filter must mitigate the resulting resonance and the distortion in the whole range of expected harmonic. For the filter design a complete harmonic analysis of the industrial power system was carried out. A fine tuning around 5.5th and 12th orders results from a tradeoff between reducing the harmonic distortion at six-pulse operation (5th, 7th, 11th, and 13th) and avoiding negative effects at integer harmonic frequencies, namely, 2nd, 3rd, and 4th. Fig. 9 shows the structure of the filter and the behavior of its impedance. The designed values are shown in Table I. This filter is connected at bus 10, as seen in Fig. 1. The use of the filter reduces drastically the bus impedance around the resonance frequency, shown clearly in Fig. 8.

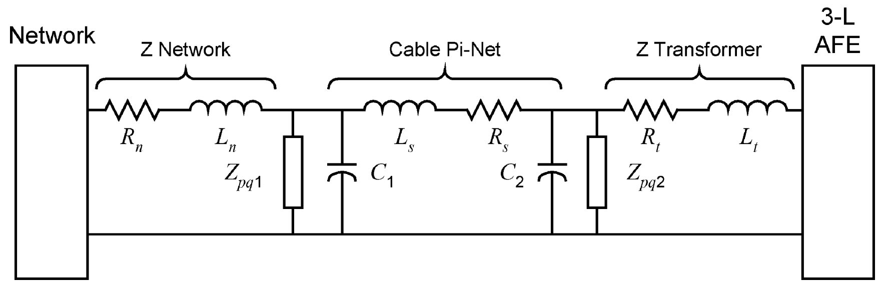

Fig. 7. Simplified electrical circuit used to supply one AFE.

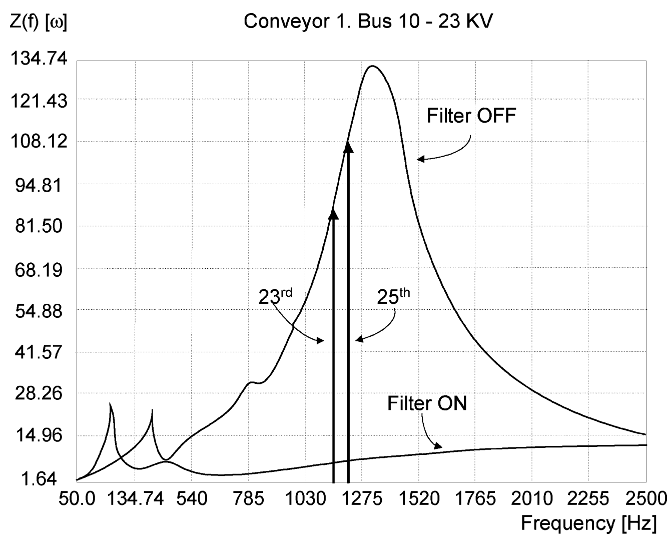

Fig. 8. Impedance $Z(f)$ at bus 10.

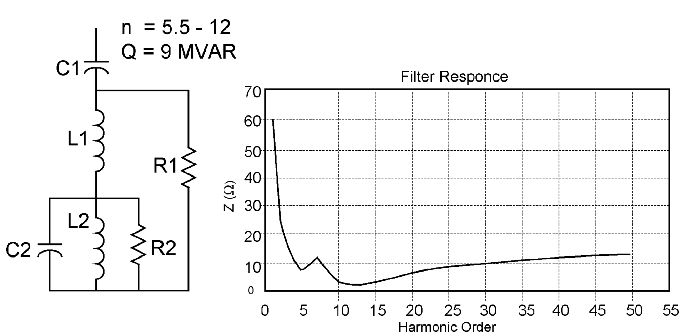

Fig. 9. Conveyor filter structure and frequency response. Filter is tuned to harmonics 5.5 and 12.

TABLE I
FILTER COMPONENT VALUES

Component	Value	Rated conditions
C1	53.3 uF	Rated Voltage 33kV
L1	1.74 mH	Rated fundamental current: 260 A. Rated Current at 275 Hz: 230 A.
R1	15 Ohms	75 kW
L2	1.09 mH	Rated fundamental current: 270 A. Rated current at 600 Hz: 430 A.
C2	233 uf	5kV
R2	12 ohms	75 kW

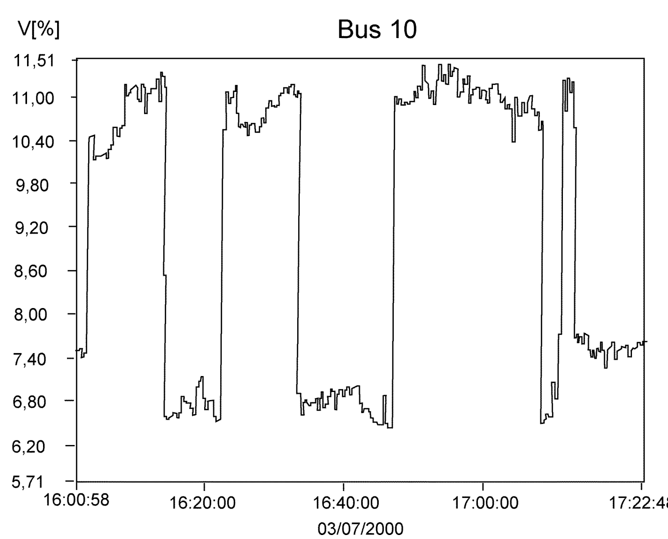

Fig. 10. Measured distortion (THD_v) of bus 10 without conveyor filter.

VI. Operational Results

The simulation studies revealed the presence of the resonance and permitted the design of the filter to solve the problem. Here, two significative results are presented. The first one, Fig. 10, shows the result of harmonic interaction with the cables when no filter is connected. This figure presents the measured total harmonic voltage distortion (THD_v) for bus 10 and tie-breaker open for the system shown in Fig. 1, without filter and for different loading conditions of the conveyors. The technical specification established that the THD_v should not exceed the limit of 5% under normal operating conditions. It can be seen in Fig. 10 that the THD_v without filter is always 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 filter of the conveyor is connected. The distortion is reduced to a value of $\mathrm{THD}_v = 01.74\%$, which is smaller than the limit of 5%. In addition, with the filter there are no disturbances during the starting phase of the conveyor.

VII. Conclusion

Key aspects related to 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 work allows 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 a smooth behavior of the belt.

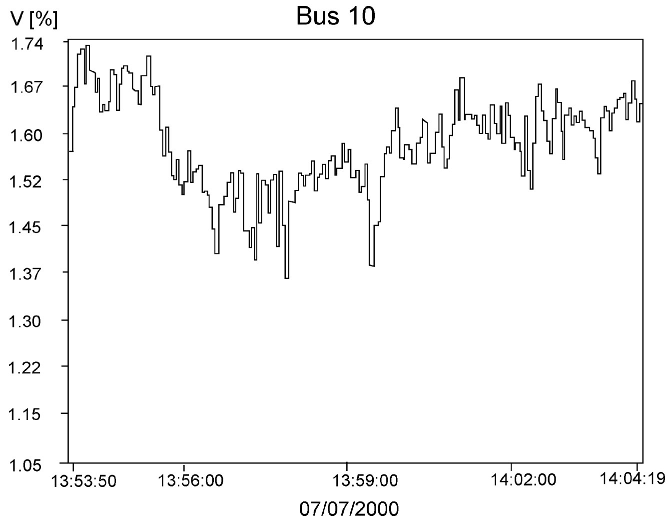

Fig. 11. Measured distortion (THD_v) of bus 10 with conveyor filter.

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

The use of SHE and wye–delta connection at the input transformer (12-pulse configuration) allows for the effective elimination of low-order harmonics, working with a very reduced switching frequency.

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

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

The conveyor has been successfully erected and commissioned and has now more than four years of satisfactory operation at rated conditions, transporting 5800 t/h and generating a total power of 15 MW with power factor near unity.

REFERENCES

[1] E. Cereceda, "Production of Los Pelambres starts in 3 months" (in Spanish), *Chilean Mining J.*, no. 217, pp. 7–15, Jul. 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/Jun. 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. Appl.*, vol. 38, no. 1, pp. 203–210, Jan./Feb. 2002.

[4] J. Pontt, E. Perelli, and C. Pontt, "Harmonix: A software package for teaching harmonic in power systems," in *Proc. 7th Eur. Conf. Power Electronics and Applications, EPE'97*, Trondheim, Norway, Sep. 1997, pp. 4.996–4.999.

[5] T. Salzmann, G. Kratz, and C. Däubler, "High-power drive system with advanced power ciruitry and improved digital control," *IEEE Trans. Ind. Appl.*, vol. 29, no. 1, pp. 168–174, Jan./Feb. 1993.

[6] J. Pontt, J. Rodríguez, R. Huerta, and J. Pavez, "Mitigation of noneliminated harmonics of SHEPWM three-level multipulse three-phase active front end converters with low switching frequency for meeting standard IEEE519–92," in *Proc. IEEE Power Electronics Specialists Conf., PESC'03*, Jun. 15–19, 2003, pp. 531–536.

[7] *Ley General De Servicios Eléctricos (General Law for Electrical Systems) D. S. No. 327*, Ministerio De Minería, Chile, Sep. 1998.

[8] *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, ANSI/IEEE Std 519-1992.

[9] S. A. Pignari and A. Orlandi, "Long-cable effects on conducted emissions levels," *IEEE Trans. Electromagn. Compat.*, vol. 45, no. 1, pp. 43–54, Feb. 2003.

[10] A. F. Moreira, T. A. Lipo, G. Venkataramanan, and S. Bernet, "High-frequency modeling for cable and induction motor overvoltage studies in long cable drives," *IEEE Trans. Ind. Appl.*, vol. 38, no. 5, pp. 1297–1306, Sep./Oct. 2002.

[11] A. Nabae, I. Takahashi, and H. Akagi, "A new neutral-point-clamped PWM inverter," *IEEE Trans. Ind. Appl.*, vol. IA-17, no. 5, pp. 518–523, Sep./Oct. 1981.

[12] J. Holtz, "Pulsewidth modulation for electronic power conversion," *Proc. IEEE*, vol. 82, no. 8, pp. 1194–1214, Aug. 1994.

[13] A. Mertens, R. Sommer, and C. Brunotte, "Applications of medium voltage drives with IGBT three-level inverter," in *Proc. IEE Seminar PWM Medium Voltage Drives (Ref. 2000/063)*, 2000, pp. 7/1–7/14.

[14] K. O'Brien, R. Teichmann, and S. Bernet, "Active rectifier for medium voltage drive systems," in *Proc. 16th Annu. IEEE Applied Power Electronics Conf. and Exhibition, APEC'01*, vol. 1, Anaheim, CA, Mar. 4–8, 2001, pp. 557–562.

José R. Rodríguez (M'81–SM'94) received the Engineer degree from the Universidad Técnica Federico Santa Maria, Valparaíso, Chile, in 1977, and the Dr.-Ing. degree from the University of Erlangen, Erlangen, Germany, in 1985, both in electrical engineering.

Since 1977, he has been with the Universidad Técnica Federico Santa Maria, where he is currently a Professor and Academic Vice-Rector. During his sabbatical leave in 1996, he was responsible for the mining division of Siemens Corporation in Chile. He has several years consulting experience in the mining industry, especially in the application of large drives such as cycloconverter-fed synchronous motors for SAG mills, high-power conveyors, controlled drives for shovels, and power quality issues. His research interests are mainly in the areas of power electronics and electrical drives. In recent years, his main research interests are in multilevel inverters and new converter topologies. He has authored or coauthored more than 130 refereed journal and conference papers and contributed to one chapter in the *Power Electronics Handbook* (New York: Academic, 2001).

Jorge Pontt (M'00–SM'04) received the Engineer and Master degrees in electrical engineering from the Universidad Técnica Federico Santa María (UTFSM), Valparaíso, Chile, in 1977.

Since 1977, he has been with UTFSM, where he is currently a Professor in the Electronics Engineering Department and Director of the Laboratory for Reliability and Power Quality. He is coauthor of the software Harmonix used in harmonic studies in electrical systems. He is the coauthor of patent applications concerning innovative instrumentation systems employed in high-power converters and large grinding mill drives. He has authored more than 90 international refereed journal and conference papers. He is a Consultant to the mining industry, in particular, in the design and application of power electronics, drives, instrumentation systems, and power quality issues, with management of more than 80 consulting and R&D projects. He has had scientific stays at the Technische Hochschule Darmstadt (1979–1980), University of Wuppertal (1990), and University of Karlsruhe (2000–2001), all in Germany. He is currently Director of the Centre for Semiautogenous Grinding and Electrical Drives at UTFSM.

Rodrigo Huerta received the Electronic Engineer degree from the Universidad Técnica Federico Santa María (UTFSM), Valparaíso, Chile, in 2002.

He was a Professor of Digital Signal Processing at UTFSM, where he also conducted research as part of the Power Electronics Team. His research focus is digital signal processing applied to power electronics. Recently, he joined the ESO-Paranal Observatory, Antofagasta, Chile, as an Electronics Engineer.

Gerardo Alzamora received the Ingeniero Civil Electricista degree from the Universidad Técnica Federico Santa María, Valparaíso, Chile, in 1985.

In 1985, he joined Antofagasta Minerals. Since 1992, he has been responsible for the electrical portion of the mining project "Los Pelambres" in Chile. Since 1995, he has been the Head of the Electrical Department, Compañía Minera Los Pelambres, Salamanca, Chile.

Norbert Becker studied electrical engineering (power electronics and drives) at the University of Paderborn, Soest, Germany.

In 1984, he joined Siemens AG, Erlangen, Germany, as a Commissioning Engineer in the field of open-cast mining equipment. Since 1994, he has been a Project Manager for the Sales Department of open cast mining, where, in 1995, he became Director.

Samir Kouro (S'04) was born in Valdivia, Chile, in 1978. He received the Engineer and M.Sc. degrees in electronics engineering in 2004 from the Universidad Técnica Federico Santa María (UTFSM), Valparaíso, Chile, where he is currently working toward the Ph.D. degree.

In 2004, he joined the Electronics Engineering Department, UTFSM, as a Research Assistant. His main research interests are power electronics and adjustable-speed drives.

Patricio Cortés (S'05) was born in Valparararaíso, Chile, in 1977. He received the Engineer and M.Sc. degrees in 2004 from the Universidad Técnica Federico Santa María (UTFSM), Valparaíso, Chile, where he is currently working toward the Ph.D. degree.

Since 2000, he has been with the Department of Electronics, UTFSM, where, since 2003, he has been a Research Assistant.

Pablo Lezana was born in Temuco, Chile, in 1977. He is currently working toward the Ph.D. degree in power electronics at the Universidad Técnica Federico Santa María, Valparaíso, Chile.

His research interests include PWM rectifiers and modern digital devices.