Operation of Two 6-Pulse High-Power Active-Front-End Three-Level Three-Phase Inverters in a 12-Pulse connection

J.Pontt, J.Rodríguez, A.Orellana, R. Benavides, R. de Solminihac, M. Braun (*)
Departamento de Electrónica -Universidad Técnica Federico Santa María
Casilla 110-V, Valparaíso, Chile, E-Mail : jpo@elo.utfsm.cl

(*) Elektrotechnisches Institut – Universität Karlsruhe (TH)
Kaiserstrasse 12, 76128 Karlsruhe, Germany

***Abstract* - The operating behavior of Two 6-Pulse High-Power Active-Front-End Three-Level Three-Phase Inverters in a 12-Pulse connection, concerning the harmonic network interaction for stationary regenerative operation is presented. A strategy based on a synchronous modulation method with harmonic elimination and DC-Link Voltage regulation for improving the network interaction is discussed.**

***Index Terms* - Drives, Harmonics, Multilevel converters.**

I. Introduction

Active-Front-End (AFE) Three-Level PWM Inverter Drives applications are growing because of the inherent advantages for Medium Voltage installations with 4-Quadrant and high dynamic capabilities. For high-power applications, the thermal and voltage operating conditions of power semiconductors are key factors for assuring maintenance and reliability, especially for locations with harsh environment at high altitude like mining facilities in the mountains [1, 2, 3, 4]. Harmonic interaction and power quality are also highlighted because such locations normally have weak power distribution networks, with variable topology, stating the need of network-friendly converter-fed drives and adequate harmonic filters for stringent operating conditions. Specifications and trade-offs should be found for meeting:

◊ Unity Power Factor
◊ Lowest possible switching frequency
◊ Lowest possible DC-Link Voltage and highest possible Modulation Index
◊ Reduced Harmonic injection to the network
◊ Good matching of the AFE-fed Drives with the network system.
◊ Avoiding or reducing the need of Harmonic filters.

For an application of a regenerative multidrive conveyor system with combination of two drives, each pair of 2 drives is fed by transformer windings with 30° Phase displacement for a 12-Pulse connection, which gives basically the reduction of 5, 7, 17, 19th order injection. Optimized pulse pattern could also eliminate the 11th, 13th, 23rd, 25th [3]. However, for keeping a low switching frequency in AFE-GTO-Converters, it is desirable to have a switching pattern of only 3 switching angles, for reducing the 11th and 13th order. Concerning reliability, thermal factors, voltage stressing and eventual cosmic ray stability [5], a high modulation index is desired for keeping the lowest possible DC-Link voltage for reducing the voltage stressing and switching losses. Therefore, the problem to be faced is the network interaction of the remaining 23rd and 25th and higher orders, especially with network's resonance caused by long cables [2]. The aim of this work is to develop a strategy for improving the harmonic voltage and current injection profile to the mains.

II. System Description

The fig. 1 depicts a Two-Drive system as a part of an actual multidrive industrial system intended for regenerative operation mode [4], [7]. The 12-Pulse AFE Converter system is built with Two 6-Pulse Three-Level inverter drives [1], using transformers with star-star and star-delta connection in order to cancel the 6-Pulse characteristic harmonics components. For simplicity, the 23 kV power network is supposed to be ideal, without harmonic filters, the transformers are of 2.5 MVA, Z_k=10%, 23/3.3 kV and ideal DC-Link Voltage. The study is based on a modelling and simulation with the software MatLab-Simulink .

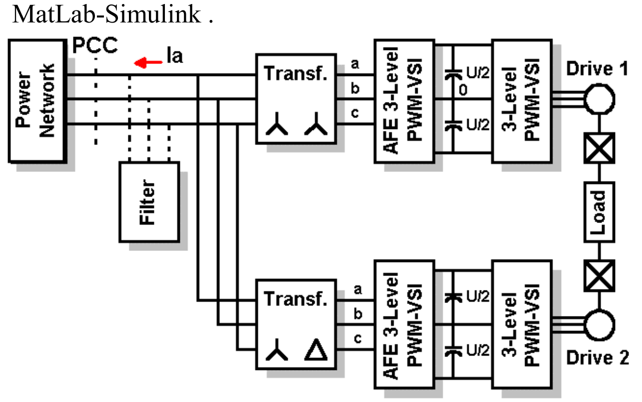

Fig. 1 12-Pulse AFE System with Two 6-Pulse 3-Level Inverter Drives

III. SWITCHING PATTERN FOR HARMONIC ELIMINATION

A. Modulation method

For Medium Voltage high power drives, a synchronous modulation with selective harmonic elimination is employed [6]. Fig.2 shows the switching pattern with 3 angles with $\pi/2$ symmetry, where the amplitude of the harmonic component of order n for the Voltage Vao is described by (1). The switching angles are calculated for commanding the fundamental component (modulation index) and for eliminating the harmonics 11^{th} and 13^{th}, by solving the equation system (2) - (4).

$$V_n = \frac{4 \cdot Vdc}{\pi \cdot n}\left[\cos(n\alpha_1) - \cos(n\alpha_2) + \cos(n\alpha_3)\right] \qquad (1)$$

$$V_1 = \frac{4 \cdot Vdc}{\pi}\left[\cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3)\right] = \frac{4 \cdot Vdc}{\pi} \cdot M \qquad (2)$$

$$V_{11} = \frac{4 \cdot Vdc}{\pi \cdot 11}\left[\cos(11\alpha_1) - \cos(11\alpha_2) + \cos(11\alpha_3)\right] = 0 \qquad (3)$$

$$V_{13} = \frac{4 \cdot Vdc}{\pi \cdot 13}\left[\cos(13\alpha_1) - \cos(13\alpha_2) + \cos(13\alpha_3)\right] = 0 \qquad (4)$$

B. Calculation of the switching angles

The corresponding non-linear equations are solved using iterative calculations. Because of multiple solutions, lowest values are selected with the relation $\alpha_1 \le \alpha_2 \le \alpha_3$. One set of the calculated solutions is depicted in the graph of fig. 3 for a range of **M** between 0.82 and 1, where **M**=1 is defined for 1 for $\alpha_1 = \alpha_2 = \alpha_3 = 0$ (block voltage operation). Fig. 3 shows the switching angles values for Voltage harmonic elimination of orders 11^{th} -13^{th}. For the region of **M** near 1 a 2-Angle scheme with $\alpha_1 = 0$ was considered.

C. Remaining harmonics of order 23^{rd} and 25^{th}

The components of order $6k \pm 1$ with k odd (orders 5, 7, 17, 19..), are cancelled because of the 12-Pulse connection. So, the components 23^{rd} and 25^{th} remain and the purpose of this work is to show how to deal with. Fig. 4 shows the normalized amplitude for Voltage harmonic components of orders 23^{rd} -25^{th}. As reference for the normalization, the ideal harmonic value for block voltage operation is considered.

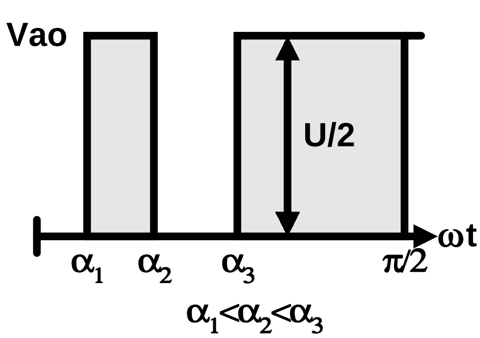

Fig. 2. Switching pattern $V_{ao}(t)$ 3-level inverter with $\pi/2$ symmetry.

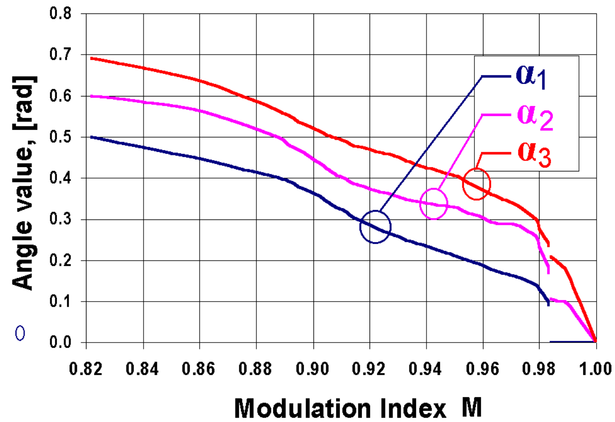

Fig. 3 Switching angles v/s Modulation index **M** for elimination of harmonic orders 11^{th} and 13^{th}

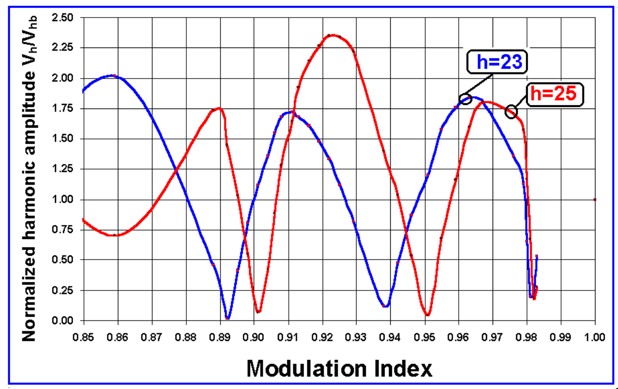

Fig. 4 Amplitude of the remaining harmonics of orders 23rd and 25^{th}

IV. HARMONIC VOLTAGE INJECTION OF ORDER 23^{RD} -25^{TH}

From Fig. 4 it can be observed that the remaining harmonic injection of orders 23^{rd} and 25^{th} depend strongly on the modulation index **M**. Looking for reducing the harmonic injection, it can be established the favorable and unfavorable working conditions for the remaining harmonic injection of orders 23^{rd} and 25^{th} . So, the tables I and II illustrate some of the best- and worst operating conditions. From the Table I and Table II, it can be seen that **M**=0.982 is the best working condition, reducing simultaneously the 23^{rd} and 25^{th} harmonic injection.

For regenerative power flow with nominal network current and voltage, a different modulation index means also a corresponding DC Link Voltage.

Table I

Best case for minimizing the 23^{rd} and 25^{th} harmonic voltage injection

M	α_1	α_2	α_3	5	7	17	19	23	25
0.982	0.11	0.199	0.253	0.61	0.34	0.28	0.40	0.21	0.19

Table II

Unfavorable working conditions for 23^{rd} harmonic voltage injection

M	α_1	α_2	α_3	5	7	17	19	23	25
0.859	0.45	0.566	0.639	0.68	0.56	1.05	0.51	2.02	0.70
0.911	0.32	0.400	0.490	0.38	0.64	0.66	0.27	1.72	1.64
0.963	0.18	0.294	0.360	0.29	0.04	0.29	0.88	1.84	1.60

V. Results for Best Working Condition

For the best working condition, Fig. 5 presents the resulting network current **Ia** of the 12-Pulse connection of Two 6-Pulse AFE Inverters for M=0.982, with a total harmonic current distortion of 3.1%. Fig. 6 and 7 show the behavior of the current contribution of Ia from both AFE-Transformers star-star and star-delta connection, respectively. DC Link voltage, U/2=2166 [V].

Fig. 8, 9, 10 depicts the harmonic spectra of the Network current Ia and the contribution of both AFE-Transformers star-star and star-delta connection, respectively.

Fig. 11 and 12 show the AFE Voltage Vab and Va at the 3.3 kV side of transformers Star-Delta and Star-Star, both with a total voltage distortion of 19.7%, respectively together with the Network phase voltage Ea, for M=0.982. The spectrum of voltage **Va** is shown in Fig. 13.

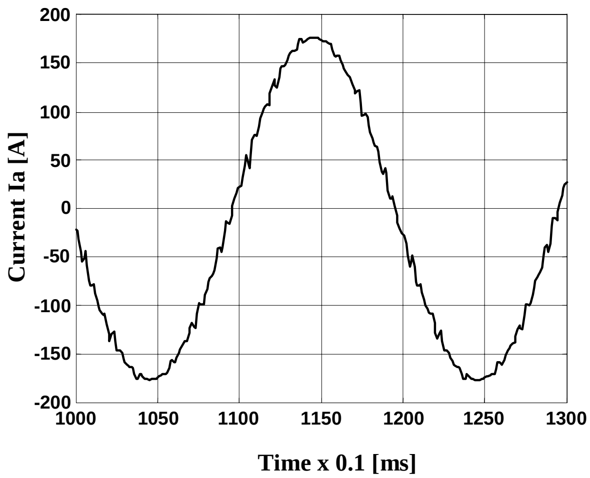

Fig.5 Network current Ia for **M**=0.982. THDi =3.1%

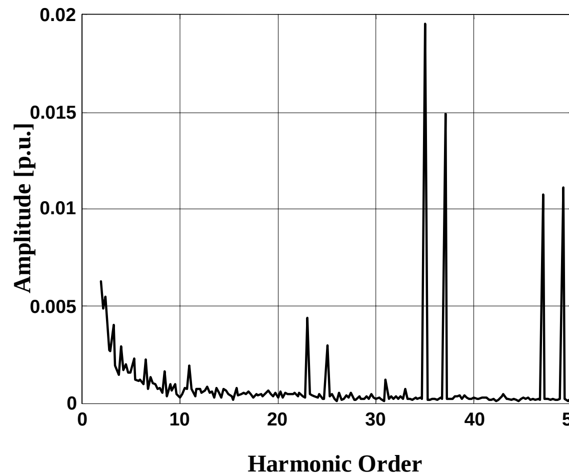

Fig.8 Spectrum of Network current Ia for **M**=0.982

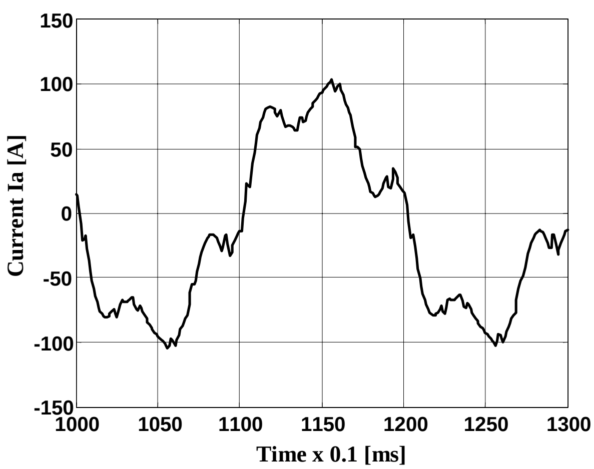

Fig.6 Line current Ia of transformer connection Star-Star. THDi = 25.5%

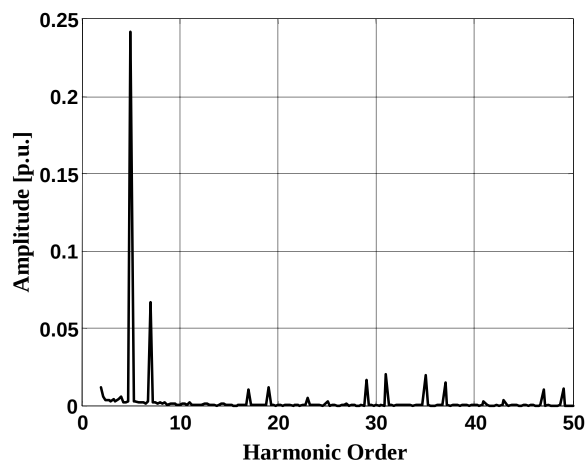

Fig.9. Spectrum of current Ia of transformer Star-Star for **M**=0.982

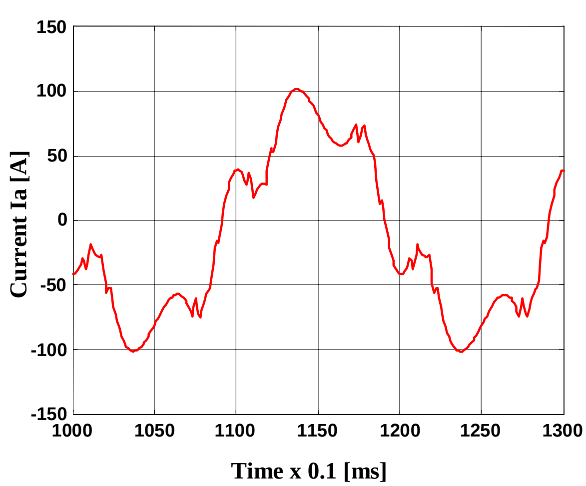

Fig.7 Line current Ia of transformer connection Star-Delta THDi = 26.2%

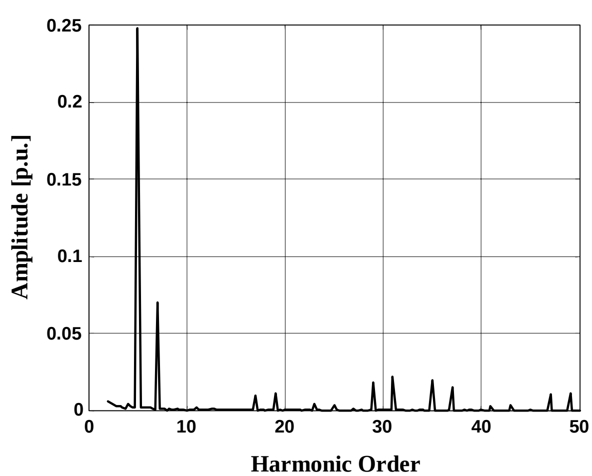

Fig. 10. Spectrum of current Ia of transformer Star-Delta for **M**=0.982

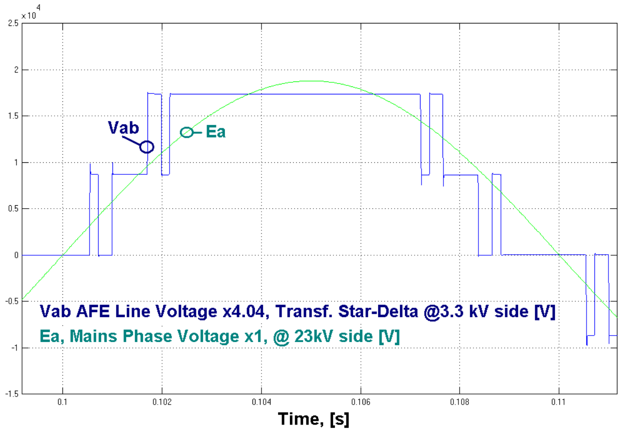

Fig. 11. AFE Voltage **Vab** at the 3.3 kV side of transformer connection Star-Delta and Network phase voltage Ea, **M**=0.982

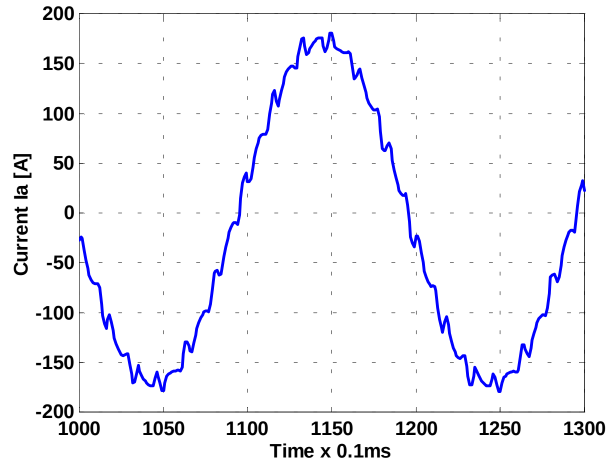

Fig. 14 Network current Ia for **M**=0.859. THDi=5.4%

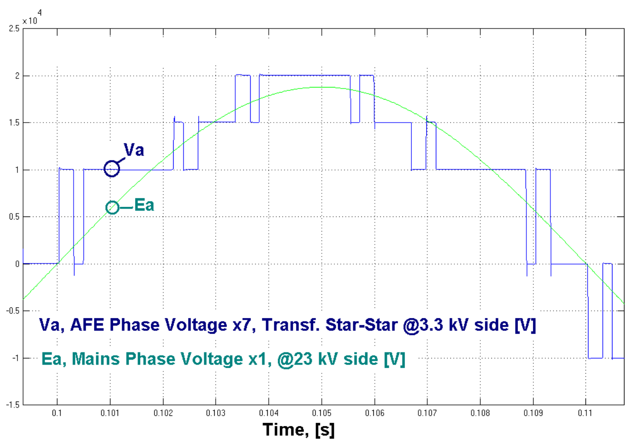

Fig. 12. AFE Voltage **Va** at the 3.3 kV side of transformer connection Star-Star and Network phase voltage Ea, **M**=0.982

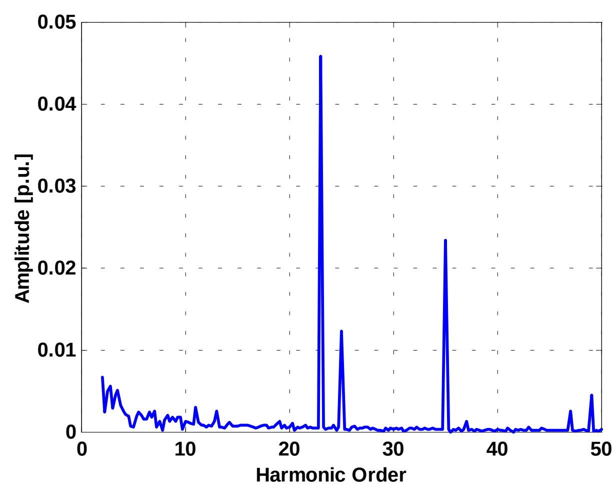

Fig. 15 Spectrum of Network current Ia for **M**=0.859

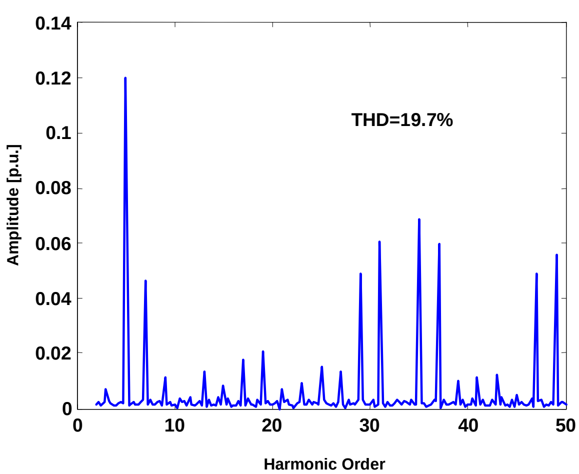

Fig. 13. Spectrum of AFE Voltage **Va** at the 3.3 kV side of transformer connection Star-Star and Network phase voltage Ea, **M**=0.982

VI. Results for Unfavorable Working Conditions

From Table II it can be seen that the worst case for the 23rd harmonic voltage injection is **M** = 0.859, with a normalized amplitude of 2.02, DC Link voltage, U/2=2476 [V]. Fig. 14 shows the resulting network current Ia and the Fig. 15 depicts its harmonic behavior with a total current distortion of 5.4%. Concerning the individual harmonic distortion for the orders 23rd and 25th, by comparison of figures 8 and 15 it is confirmed that for **M**=0.859, this distortion is about 10 times bigger than the case for **M**=0.982. If it is not always possible to keep the modulation index **M**=0.982, other favorable values should be employed in order to avoid unfavorable working points.

The 6-Pulse characteristic harmonic current components of order 6k ±1 with k odd, produce losses in the transformers. One alternative for improving this aspect is using only one Two-Windings transformer for both drives. For an actual drive system it was chosen the scheme of Fig.1 because of expected reliability and maintenance.

VII. Comments and Conclusions

This work proposes an improvement in the harmonic voltage injection to the mains for High-Power Three-Level GTO-Inverter Drive in 12-Pulse connection using a switching pattern with harmonic elimination method for the 11^{th} and 13^{th} harmonic orders, employing only three control angles. For a network with a resonance behavior about the 23^{rd} harmonic order, the proposed strategy is based on controlling the DC-Link Voltage in order to keep the best working conditions for reducing the 23^{rd} harmonic injection, by keeping a modulation index of 0.982. Simultaneously, the 25^{th} harmonic order is also reduced. The same strategy applies for avoiding unfavorable working conditions of modulation index of 0.859, 0.911 and 0.963. Of course, with two additional switching angles it would be possible to eliminate the components 23^{rd} and 25^{th} with the trade-off of having additional losses and cooling needs at the GTO's. Furthermore, a similar strategy can be applied for reducing the voltage injection of the 35^{th} and 37^{th} harmonic orders. Further work includes the proper analysis, design and optimization of the DC-Link voltage regulation and control loop of AFE- and motor side-inverters as well as the behavior of non-characteristic and higher harmonic components.

VIII. Acknowledgement

The authors gratefully acknowledge the sponsorship of the SEW Stiftung and DFG SFB425 for supporting this work.

IX. References

[1] A. Nabae, I. Takahashi, H. Akagi, *"A New Neutral-Point-Clamped PWM Inverter"*, IEEE-Trans. on Ind. App. Vol. IA-17, No.5, Sep/Oct., 1981, pp. 518-523.

[2] J. Pontt et Al. *Overvoltages caused by step-up transformer and long cables in medium voltage inverter drives,* Proceedings EPE'99, Lausanne, Switzerland, 1999, paper 500.pdf (CD-Proceedings).

[3] A. Mertens, R. Sommer, C. Brunotte, *Applications of Medium Voltage Drives with IGBT Three-Level Inverter,* PWM Medium Voltage Drives (Ref. No. 2000/063), IEE Seminar, 2000 Page(s): 7/1 -7/4.

[4] J. Rodríguez, J. Pontt, N. Becker, A. Weinstein, *Regenerative Drives in the Megawatt Range for High Performance Downhill Belt Conveyors, Proceedings* 2000 IEEE Industry Application Conference, 35^{th} Annual Meeting, Roma, Italy, pp. 2707-2712.

[5] S. Eicher, S. Bernet, P. Steimer, A. Weber, *The 10kV IGCT – A new Device for Medium Voltage Drives*, Proceedings IEEE-IAS'2000, 35^{th} IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy, Roma, Italy, 8-12 Oct., 2000, pp.2859-2865.

[6] K.O'Brien, R. Teichmann, S. Bernet, *Active Rectifier for Medium Voltage Drive Systems*, Proceedings of 16^{th} Annual IEEE Applied Power Electronics Conference and Exhibition, Anaheim, California, USA, 4-8 March, (APEC'2001), paper S16p1.pdf.

[7] J. Pontt, M. Braun, A. Orellana, *Harmonic Interaction of Active-Front-End Three-Level Inverters operating in a weak network with long cables,* European Power Electronics Conference EPE'2001, Graz, Austria, 26-29 Aug., 2001, paper PP00113.