PWM Method to Eliminate Power Sources in a Nonredundant 27-Level Inverter for Machine Drive Applications

Mauricio Rotella, Gonzalo Peñailillo, Javier Pereda, and Juan Dixon, *Senior Member, IEEE*

***Abstract*—A nonredundant three-stage 27-level inverter using "H" converters is analyzed for medium- and high-power machine drive applications. The main advantage of this converter is the optimization of levels with a minimum number of semiconductors. However, the system needs six bidirectional and isolated power supplies and three more unidirectional if the machine is not using regenerative braking. In this paper, these nine power supplies are reduced to only four, all of them unidirectional, using three strategies: 1) the utilization of independent and isolated windings for each phase of the motor; 2) the utilization of independent input transformers; and 3) the most important of them, the application of special pulsewidth modulation (PWM) strategies on the 27-level converter, to keep positive average power at the medium power bridges and zero average power at the low-power bridges. The generation of this PWM and control of this multiconverter was implemented using DSP controllers, which give flexibility to the system.**

***Index Terms*—Drives, multilevel systems, pulsewidth-modulated power converters.**

I. INTRODUCTION

PULSEWIDTH modulation (PWM) techniques used today to control modern static converters such as high-power machine drives, strongly depend on switching frequency of the power semiconductors. Normally, voltage moves to discrete values, forcing the design of machines with good isolation, and sometimes loads with inductances in excess of the required value. In other words, neither voltage nor current is as expected. This also means harmonic contamination, additional power losses, high-frequency noise, and inverter-induced bearing currents that increase the maintenance problems of the drive [1], [2]. All these reasons have generated many research works on the topic of PWM modulation [3]–[7]. More recently, cascade multilevel converters [8]–[12] have permitted to have many levels or steps of voltage to reduce the total harmonic distortion (THD) levels. However, these converters have a big drawback: many isolated power supplies are required to get a good voltage waveform. A special kind of multilevel arrangement, using asymmetric H-bridges with nonredundant levels of voltage [13] has recently been investigated. Some advantages of these converters are the following: optimized number of levels, very low THD, reduced dv/dt, almost negligible common-mode voltage, smaller output filter, reduced volume and cost, better reliability, and lower switching losses. Some drawbacks are loss of modularity (bridges have to be made for different voltage levels) and many floating dc sources. Under certain applications, like constant frequency operation (rectifiers, power compensators, or active filters), this kind of arrangement can use only one dc source because output transformers can be utilized [14]–[18]. Nevertheless, for machine drives, output transformers cannot be used due to problems at very low-frequency operation. Then, the large number of floating power supplies previously mentioned is more difficult to reduce. Besides, most of them need to be regenerative (bidirectional). For this reason, costly regenerative rectifiers with input transformers or diode rectifiers with dissipative elements have to be implemented to solve that drawback [17]–[22]. Typically, an asymmetrical 27-level inverter for machine drives needs three independent power supplies per phase. If the drive is not regenerative, six of these power supplies must be bidirectional and the other three can be unidirectional. Then, the reduction of these power supplies is an important fact.

The purpose of this paper is to describe a special control and hardware strategies to reduce the nine power supplies to only four, all of them unidirectional. These special control and hardware strategies are the following: a) the use of independent and isolated windings for each phase of the motor [23]; b) the utilization of independent input transformers; and c) the most important of them, the application of special PWM strategies to keep positive average power at the medium power bridges, and zero average power at the low-power bridges.

II. BASICS OF MULTISTAGE CONVERTERS

A. Basic Principle

Fig. 1 shows the main components of a 27-level converter using "H"-bridges. The figure only shows one of the three phases of the complete system. As shown, the dc power supplies of each one of the three converters are isolated and needs to be bidirectional. Besides, the dc supplies are scaled with levels of voltage in power of three. The scaling of voltages in power of three allows having, with only three converters, $3^3 = 27$

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M. Rotella is with ABB S.A., Santiago 7780006, Chile (e-mail: mauricio.rotella@cl.abb.com).

G. Peñailillo, J. Pereda, and J. Dixon are with the Department of Electrical Engineering, Pontificia Universidad Católica de Chile, Santiago 7820436, Chile (e-mail: gepenail@uc.cl; jepereda@ing.puc.cl; jdixon@ing.puc.cl).

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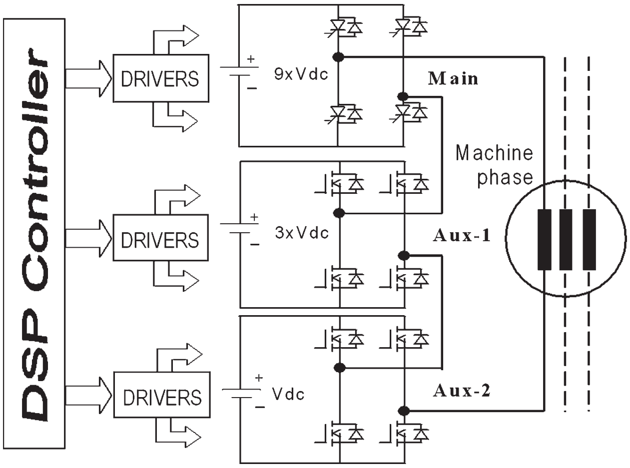

Fig. 1. Main components of the three-stage 27-level drive (one phase).

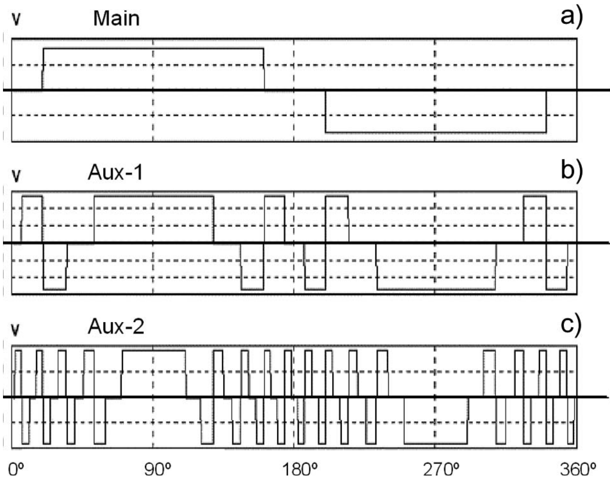

Fig. 2. Voltage modulation in each converter for one complete cycle.

different levels of voltage: 13 levels of positive values, 13 levels of negative values, and zero. The converter located at the top of the figure has the biggest voltage, and will be called main converter. The other two modules will be the auxiliary converters. The main works at a lower switching frequency and carries more than 80% of the total power, which is an additional advantage of this topology for high-power machine drives applications. Fig. 1 also shows the machine, with independent windings for each phase, to allow the utilization of only one power supply for the three main converters. With 27 levels of voltage, a three-stage converter can follow a sinusoidal waveform in a very precise way. It can control the load voltage as an amplitude modulation (AM) device. Fig. 2 shows the simulated voltage modulation in each one of the three "H" converters, for 100% AM.

B. Power Distribution

The example of Fig. 3 shows the simulated power distribution in one phase of the three-stage converter, feeding a machine with $\cos\varphi = 1$ (e.g., synchronous machine). A little more than 80% of the power is delivered by the main converters, about 15% for the Aux-1 converters, and less than 4% of the total power for Aux-2 converters. However, and despite Aux converters need low-power sources, they have to be bidirectional. There are three solutions for this problem: 1) active front-end rectifiers; 2) bidirectional dc–dc power supplies; or 3) passive rectifiers with dissipative resistors. However, as the average negative power exists only at certain levels of voltage, simple unidirectional rectifiers and special PWM modulation can be applied. This PWM modulation is based on jumping some voltage levels when average power in a period becomes negative. This solution works well for both, Aux-1 and Aux-2 converters. However, the topology for the small Aux-2 converters can be simplified a little more using only an appropriate PWM technique.

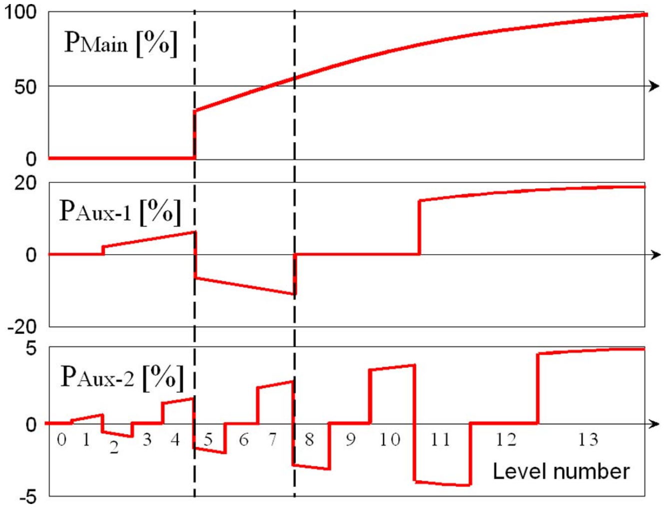

Fig. 3. Active power distribution in a three-stage converter ($\cos\varphi = 1$).

In the case of Aux-2, the power transfer is even smaller (less than 4%), and it can be managed to keep average power to zero by using high-capacity floating capacitors and a special PWM modulation, but keeping THD as small as possible.

III. INPUT POWER TOPOLOGY

Using the aforementioned strategies, Fig. 4 shows the topology of the complete power driver, including rectifiers and inverters. The H-bridges of the three main converters are fed in parallel from only one dc supply, with the transformer and rectifiers connected in series. The rectifiers are in six-pulse configuration with a four-winding transformer, to create three secondary voltage systems, one for each of the three main converters, and shifted in $+20°$, $0°$, and $-20°$.

This configuration generates a very low harmonic distortion from the main's point of view [11]. With this connection, the three windings of the machine have to be independently fed, as shown in Fig. 4. Otherwise, main bridges cannot independently work because they need to generate positive, negative, or zero voltage outputs at different times.

As shown in Fig. 4, only four independent dc power supplies are required for the complete system instead of nine. Only one for the three main converters and three more (unidirectional low power) for Aux-1 converters. The Aux-2 converters only need floating capacitors. As these two solutions need special modulation techniques to avoid power back at the Aux-1 and

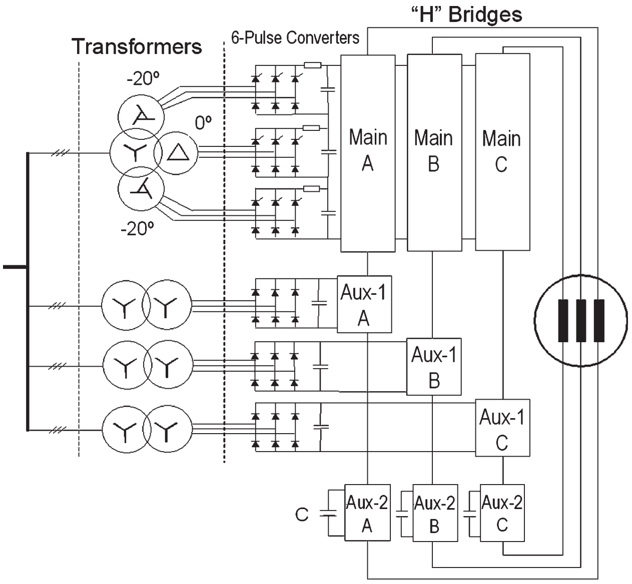

Fig. 4. Proposed topology using only four floating power supplies.

to keep zero average power at Aux-2, the next sections will explain the modulation techniques implemented in this paper.

IV. MODULATION TECHNIQUES IMPLEMENTED

Although high-quality output of multistage converters have been known for quite a while, the large part count, quantity of isolated sources, and overall system complexity have limited their use in many potential applications. Topologies with fewer components are inherently more reliable. In this section, three enhancements will be explained. The first one is the PWM applied to each possible level. This enhancement was absolutely necessary to develop the next two. The second one is a control strategy to have zero average current over Aux-2, which enables the replacement of the bidirectional sources with floating capacitors. Finally, an additional improvement in the control scheme will be presented, which eliminates the need for bidirectional sources on stage Aux-1, by keeping positive average current in all operating conditions.

A. PWM to Each Level

With three stages per phase scaled in power of three, 27 unique levels in the output voltage waveform can be generated. This amount of levels assures high-quality voltage and current waveforms for full converter voltage. When lower voltages are required at the output, for lower output frequencies in a machine drive for example, the voltage steps become larger compared to peak voltage amplitude. When this happens, the current harmonics to the motor tend to be more relevant, incrementing motor losses, audible noise, and risk of pulsating torques.

One way to overcome this limitation is to introduce PWM to each level. The benefits are more significant for lower output voltages. The disadvantage is higher switching frequency in all semiconductors but particularly in auxiliary stages. The main stage needs to be commutated in very few levels, so the average switching frequency for this level can be kept low.

B. Zero Average Power at Aux-2

The advantage of nonredundant multilevel inverter is that large quantity of level can be achieved at the output voltage with extremely low harmonic current. The biggest drawback is that for some levels, the dc current over a stage can become negative (negative power). If the average dc current for complete cycle in a particular state of operation (voltage and frequency) is negative, then is necessary to have a bidirectional dc–dc converter to withdraw the energy from the capacitor to the feeding network. This requirement adds complexity to the system. The previous Fig. 3 showed, for all three stages (main, Aux-1, and Aux-2), the active power in each converter from 0% to 100% voltage (levels 0 to 13). From this figure, it is shown that depending on the inverter operating conditions, auxiliary stages can have either positive or negative power. For the particular case of Aux-2, which manages less than 4% of the total power, the need of a power sources can be eliminated by bringing this average dc current, thus power, to zero.

As shown in Table I, the effect of the pulse is different for every level. For example, from level +5 to +6, the dc current over Aux-2 (power) is going from negative (charging) at base, to zero during the pulse. At the next output level of +7, the effect of the pulse is completely opposite going from zero current at the base and positive current during the pulse, as also shown in Fig. 3. This alternating pulse effect makes possible zero average current over Aux-2 and elimination of the source by controlling the capacitor voltage. The control block in Fig. 5 controls the dc voltage by adjusting the width of the pulses proportional to voltage error and the pulse effect in a particular output level. In the example of Fig. 6, if the voltage over the capacitor is lower than the reference, the dc voltage controller will decrease the width of the pulses on level +6 and increase them for level +7.

The additional current harmonics with this control strategy can be neglected for most of cases. For low output voltages, at least two stages have to be in operation to keep the average current zero. During the evolution of the voltage waveform, the dc voltage controller will adjust the standard PWM pattern in a way that the capacitor voltage is kept constant as shown in simulation of Fig. 7. The bigger the capacitance, the lower the ripple. Large capacitance can assure that only very small deviation to the optimum PWM is necessary, keeping the current harmonics to the minimum. However, the capacitor cannot be indefinitely enlarged and, if the converter is working at the smallest voltage (level 1 or 1/13 of full voltage for long time), the capacitor finally will not be able to keep constant voltage (will discharge). This problem represents a drawback of the system, but it has a solution. It can go to level 2 and keep the required voltage using PWM. This last attribute was not implemented but is only a matter of additional software.

C. Positive Average Power at Aux-1

Also, in Aux-1 stage, there is need for bidirectional dc source for some operating conditions, due to the negative average current. In Fig. 3, this area starts from level 5 to level 7. Then again, as done for Aux-2, the overall topology can

TABLE I
EFFECT OF A PULSE FOR EACH LEVEL, OVER POSITIVE VOLTAGE (HALF CYCLE)

Level	Vref_D	Command			I Aux 2			
Pulse	**Base**	**Main**	**Aux 1**	**Aux 2**	**Base**	**Pulse**	**Effect of a Pulse**	**IkpVdc.tbl**
					0	0	None	0
+1	**0**	0	0	1	0	+	Discharge	1
+2	**+1**	0	1	-1	+	-	Charge	-1
+3	**+2**	0	1	0	-	0	Stop Charging	1
+4	**+3**	0	1	1	0	+	Discharge	1
+5	**+4**	1	-1	-1	+	-	Charge	-1
+6	**+5**	1	-1	0	-	0	Stop Charging	1
+7	**+6**	1	-1	1	0	+	Discharge	1
+8	**+7**	1	0	-1	+	-	Charge	-1
+9	**+8**	1	0	0	-	0	Stop Charging	1
+10	**+9**	1	0	1	0	+	Discharge	1
+11	**+10**	1	1	-1	+	-	Charge	-1
+12	**+11**	1	1	0	-	0	Stop Charging	1
+13	**+12**	1	1	1	0	+	Discharge	1

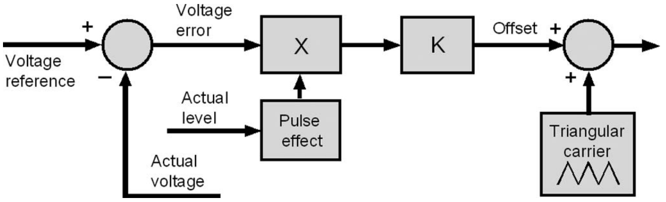

Fig. 5. Aux-2 floating capacitors voltage control.

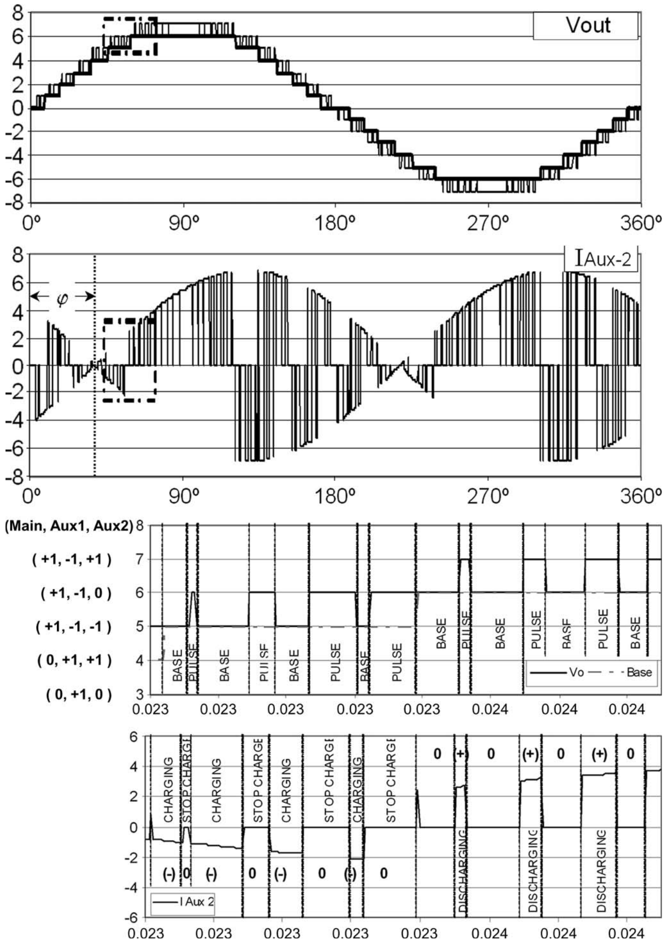

Fig. 6. Effect of a voltage pulse over Aux-2 current (I Aux 2) during levels +6 and +7.

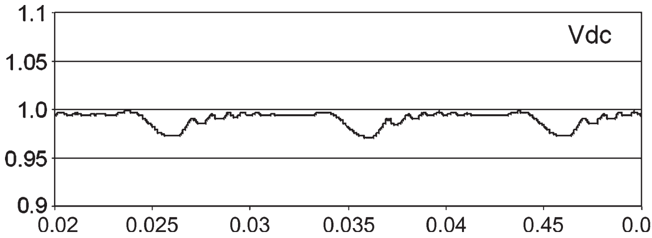

Fig. 7. Twenty-seven level output voltage, current, and dc voltage over Aux-2 floating capacitor.

TABLE II
FORBIDDEN LEVELS OF OPERATION (WHEN dc CURRENT IS REGENERATIVE) OVER AUX-1, AS A FUNCTION OF OUTPUT CURRENT I_O

To avoid forbidden levels, "jumpings" are applied (PWM between normal levels). "**F**": Forbidden Levels; "**N**": Normal Levels; "**G**": Generator (this drive never works under this condition). *Negative levels have a symmetrical behaviour.*

Level	Main	Aux1	Aux2	Io>0	Jumpings	Io<0	Jumpings
0	0	**0**	0	**N**		**N**	
1	0	**0**	1	**N**		**N**	
2	0	**1**	-1	**N**		**F**	
3	0	**1**	0	**N**		**F**	PWM
4	0	**1**	1	**N**		**F**	
5	1	**-1**	-1	**F**		**N**	
6	1	**-1**	0	**F**	PWM	**N**	
7	1	**-1**	1	**F**		**N**	
8	1	**0**	-1	**N**		**N**	
9	1	**0**	0	**N**		**N**	
10	1	**0**	1	**N**		**N**	
11	1	**1**	-1	**N**		**G**	Generator
12	1	**1**	0	**N**		**G**	Generator
13	1	**1**	1	**N**		**G**	Generator

be simplified by inhibiting negative average currents in this stage. The strategy consists on identifying the levels where the dc current becomes negative and jumping on to the next positive current level. The simulation has shown that very low additional current harmonics are generated to the motor. Table II indicates inhibited levels or jumps, which depend on Aux-1 voltage sign (+1, 0, or −1) and the direction of the output ac current Io. For example, for positive voltage (Vo) and current (Io), the jump goes from level +4 to +8. PWM is done between these

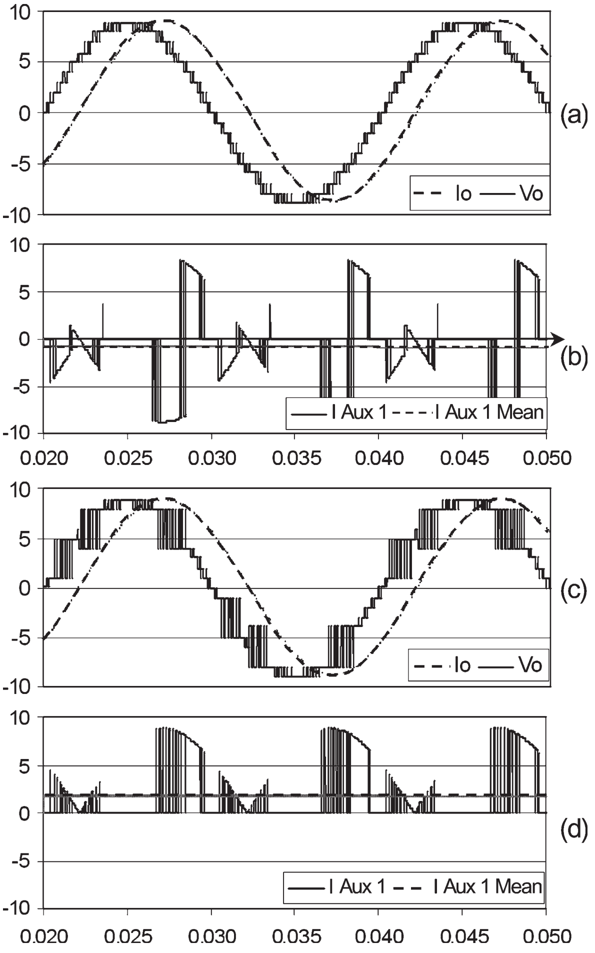

Fig. 8. Control enhancement to inhibit negative mean current. (a) Voltage and current ($\mathrm{THD} = 0.21\%$) without INC function. (b) Aux-1 current and negative average value. (c) Voltage and current ($\mathrm{THD} = 0.32\%$) with INC function active. (d) Aux-1 current and positive average value.

two levels to minimize the output current harmonics. Because of symmetry in Table II, negative levels are not displayed.

The 19 level voltage of Fig. 8(a) and (b) (70% amplitude in 27-level inverter), under normal conditions, requires a negative mean current for Aux-1. This energy can either be regenerated back to the network through a dc–dc bidirectional converter or dissipated in a resistance with a chopper. The disadvantage of both of these options is that they require additional hardware and complexity. Besides, the resistor–chopper combination is quite inefficient. Fig. 8(c) shows the modified output voltage with activated inhibit negative current (INC) function, which maintains the mean Aux-1 current positive as shown in Fig. 8(d). The solution maintains a negligible current distortion ($\mathrm{THD} = 0.32\%$) with the proposed control strategy.

V. Simulated Waveforms

The following (and also the previous) simulations were performed using PSIM, a special simulator for power electronics circuits [24]. Fig. 9 shows the three-phase output voltages and currents produced by the three-stage converter at nominal conditions and during a acceleration from 0 Hz–0 V to 50 Hz–2300 V. The machine is a 2-MW 2.3-kV 594-A 50-Hz induction motor with independent and isolated windings as shown in Fig. 3. Fig. 10 shows current harmonic distortion with and without INC function.

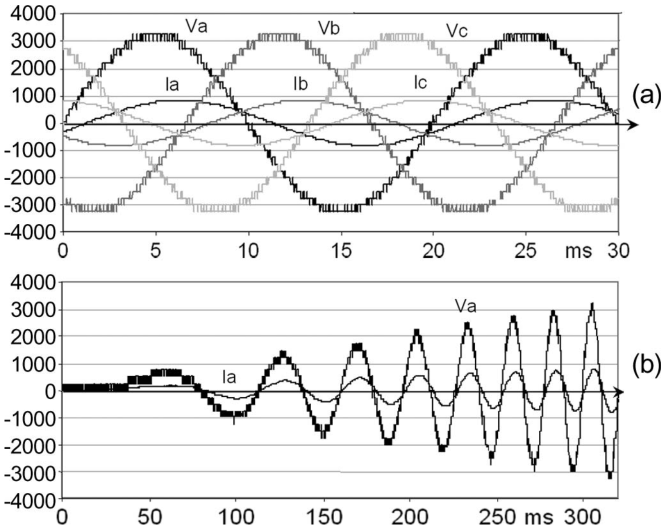

Fig. 9. Voltage and current at the motor windings. (a) Three phase at nominal conditions. (b) Single phase during an acceleration from zero to nominal operating conditions.

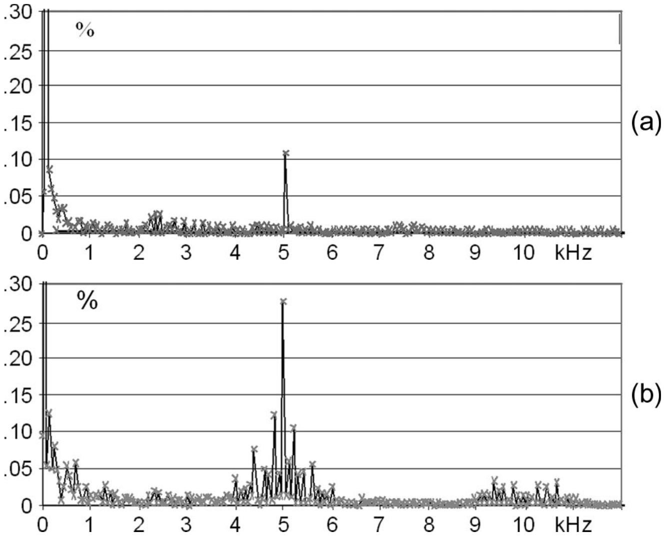

Fig. 10. Current harmonics spectrum at the motor windings at 70% of the voltage amplitude (19 levels). (a) Without INC function activated and negative mean current over Aux-1. (b) With INC function activated and positive mean current over Aux-1. Note the scale of these diagrams.

Finally, Fig. 11 shows current and voltage waveforms without and with INC function at 35% of full voltage.

VI. Experimental Results

For experiments, a small-scale 3-kW 27-level inverter using H-bridge insulated gate bipolar transistor modules was implemented. The three main bridges were connected to a common 72-Vdc power supply, and the Aux-1 converters were fed with three independent 24-Vdc unidirectional power supplies. Finally, the Aux-2 converters were implemented with floating ultracapacitors and a feedback control loop that maintains their dc voltages at 8 Vdc. These ultracapacitors do not need to be

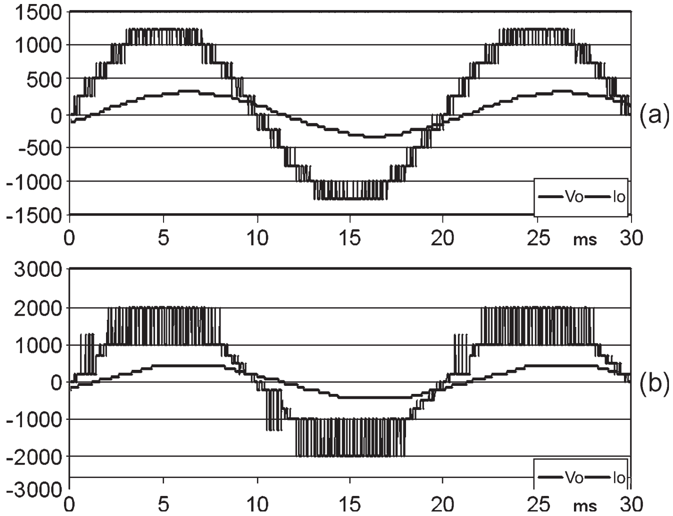

Fig. 11. Single-phase voltage and current waveforms in one of the motor windings. (a) Without and (b) with INC function at 35% of full voltage.

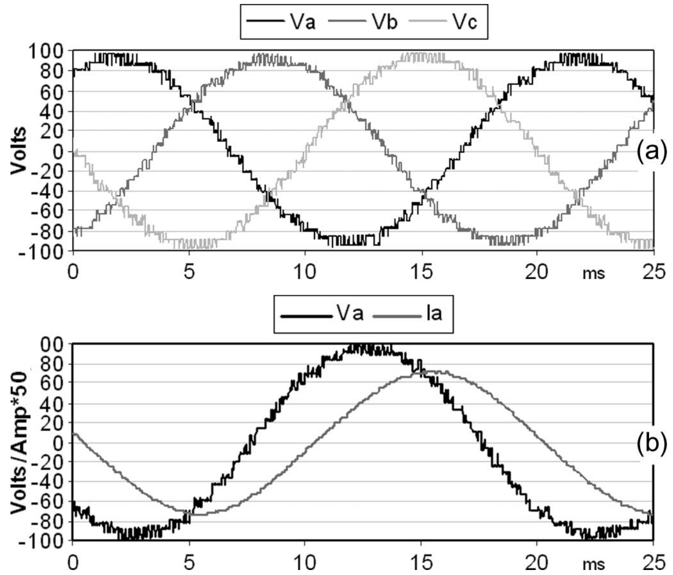

Fig. 12. Experimental oscillograms without INC function (100% voltage). (a) Three-phase voltage waveform. (b) Single phase voltage and current.

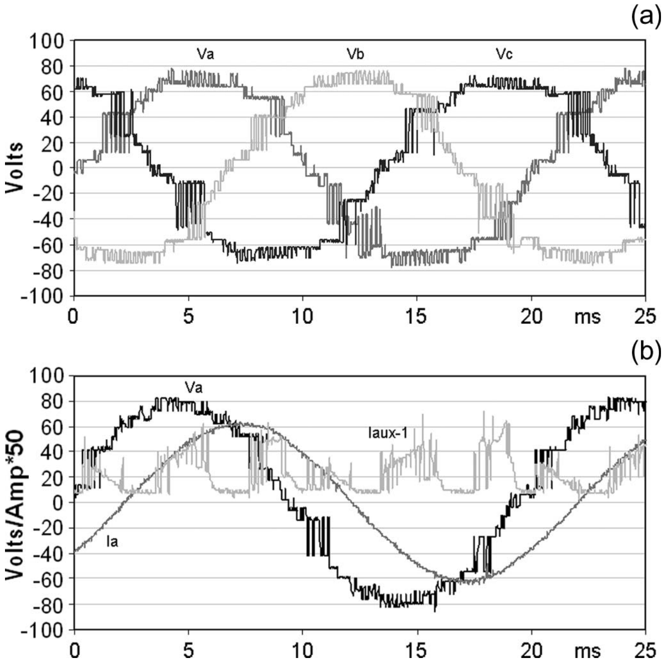

Fig. 13. Waveforms with INC function at 80% full voltage. (a) Three-phase voltage waveforms. (b) Single-phase voltage and current, and dc current from Aux-1 supply (average current positive).

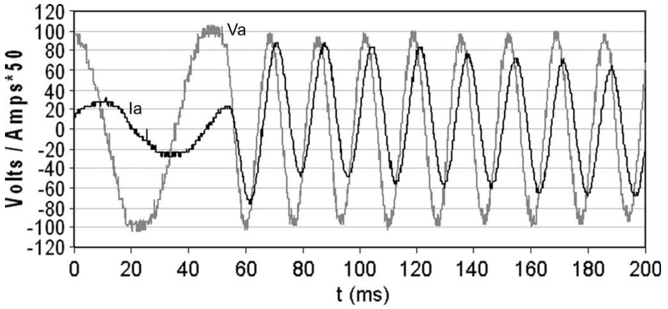

Fig. 14. Step change from 20 to 60 Hz.

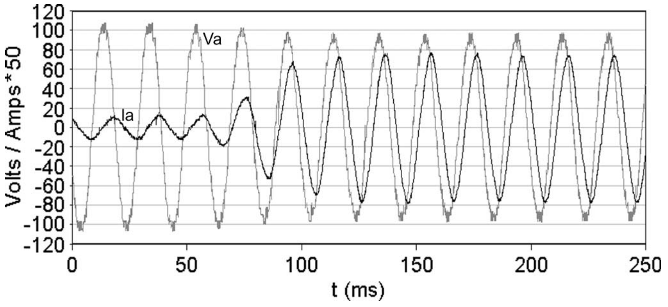

Fig. 15. Step change from zero to full load.

larger than 1 F, but 23-F devices were used because of lack of smaller capacitors. The load was a 1-kW 230-V induction machine with independent windings for each phase, as was required for the implementation of this topology (see Fig. 4).

Fig. 12(a) shows the voltage waveforms of each one of the three phases under normal operation (no jumping levels or steps). On the other hand, Fig. 12(b) shows the voltage and current in one of the phases of the inverter. It can be observed that the quality of the current is very high as expected with a 27-level inverter. Now, Fig. 13(a) shows the inverter waveforms when the INC function has been activated because the average power in the Aux-1 supply becomes negative when this function is not applied. The "jumpings" on the voltage steps are clearly present in the figure, and the current is not seriously affected. The oscillogram without negative parts is the dc link current, which is being controlled to keep positive average power at the dc link. Similarly, Fig. 13(b) shows the three-phase voltage waveforms and the jumping of voltage steps to keep in each one of the three Aux-1 converters, the required positive average power at the dc link. To simplify the comparison with Fig. 12, this figure has been done at the same frequency (50 Hz).

Fig. 14 shows a step response of the system from 20 to 60 Hz, and Fig. 15 shows a step response of the system from zero load to full load. As can be appreciated, the power converter can manage transient situations keeping the current with low harmonic distortion.

VII. CONCLUSION

A combination of topological solutions and special control strategies, to reduce and simplify power sources in a 27-level inverter for machine drive applications, has been investigated. Normally, these converters need six bidirectional, floating power supplies, and three more unidirectional if the machine is not using regenerative braking. In this paper, these nine power supplies are reduced to only four, all of them unidirectional. The circuit connections and control strategies utilized were: 1) the application of independent and isolated windings for each phase of the motor, which allows the utilization of only one power supply for the main bridges; 2) the utilization of independent input transformers; and 3) the most significant of them, the generation of special PWM strategies to keep positive average power at the medium power converters (Aux-1), and zero average power at the low-power converters (Aux-2). Simulations have shown excellent results, with only a little increment in harmonic distortion compared with the system with nine independent power supplies. The experiments in a 3-kW prototype show similar results to the ones obtained in simulations.

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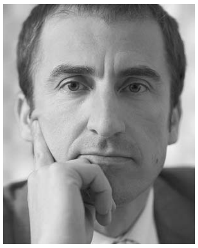

Mauricio Rotella received the Electrical Engineer Professional and the Master of Science degrees from Pontificia Universidad Católica de Chile, Santiago, Chile, in 1999 and 2006, respectively.

Since 1998, he has been with ABB S.A., Santiago, in various positions, including Product Manager for large drives for ABB Chile and Regional Sales Manager for Latin America MV Drives for ABB Switzerland. Currently, he is with the Automation Products Local Division for ABB Chile.

Gonzalo Peñailillo was born in Santiago, Chile, in 1983. He received the Civil Electrical Engineer and the Master of Science (with distinguish evaluation) degrees from the Pontificia Universidad Católica de Chile, Santiago, in 2007.

He is with the Department of Electrical Engineering, Pontificia Universidad Católica de Chile. His studies have been focused on automatic control and power electronics. He has participated in several university competitions related to electrical engineering, standing out in the Small Robots (Microbot) Competition (First Place, 2006) and in the Electric Car Competition Formula-I (Fourth Place and Best Design).

Javier Pereda was born in Santiago, Chile, in 1983. He is currently working toward the M.Sc. degree in electrical engineering at the Pontificia Universidad Católica de Chile (PUC), Santiago.

He is a Research Assistant in power electronics, electrical machines, and power generation with the Department of Electrical Engineering, PUC. His main research interests include automatic control and power electronics, specifically ac drives. He is currently working on direct torque control in multilevel inverters using an ABB industrial controller.

Mr. Pereda is a member of the Núcleo Electrónica Industrial y Mecatrónica (NEIM), Chile.

Juan Dixon (M'90–SM'95) was born in Santiago, Chile. He received the degree in electrical engineering from the Universidad de Chile, Santiago, in 1977, and the M.Eng. and Ph.D. degrees from McGill University, Montreal, QC, Canada, in 1986, and 1988, respectively.

In 1976, he was working with the State Transportation Company in charge of trolleybuses operation. In 1977 and 1978, he was with the Chilean Railways Company. Since 1979, he has been with the Department of Electrical Engineering, Pontificia Universidad Católica de Chile, Santiago, where he is currently a Professor. He has presented more than 70 works at international conferences and has published more than 30 papers related to power electronics in IEEE TRANSACTIONS and *IEE Proceedings*. His main areas of interest are in electric traction, power converters, pulsewidth modulation rectifiers, active power filters, power factor compensators, and multilevel and multistage converters. He has performed consulting work related to trolleybuses, traction substations, machine drives, hybrid electric vehicles, and electric railways. He has created an electric vehicle laboratory, where he has built state-of-the-art vehicles using brushless dc machines with ultracapacitors and high-specific-energy batteries.