High-Power Machine Drive, Using Nonredundant 27-Level Inverters and Active Front End Rectifiers

Juan Dixon, Alberto A. Bretón, Felipe E. Ríos, José Rodríguez, Jorge Pontt, *Senior Member, IEEE*, and Marcelo A. Pérez

***Abstract*—A nonredundant 27-level inverter using "H" converters is being analyzed for high power machine drive applications. The main advantage of this kind of converter is the minimum harmonic distortion obtained at the machine side. The drawbacks are the large number of isolated dc power supplies required for each one of the three stages of the multistage converter. In this paper this problem has been overcome in two ways: 1) by using independent windings for each phase of the motor and 2) by using independent input transformers. Special configurations and combinations of diode rectifiers and active front end rectifiers for one of the stages of the drive are used to eliminate input harmonics. The topology can also keep high power factor at the input terminals. Simulation results are shown and some experiments with small three-stage prototype are displayed. The control of this multiconverter is being implemented using DSP controllers, which give flexibility to the system.**

***Index Terms*—Author, please supply your own keywords or send a blank e-mail to keywords@ieee.org to receive a list of suggested keywords.**

I. INTRODUCTION

POWER electronic devices contribute with important part of harmonics in all kinds of applications, such as power rectifiers, thyristor converters, and static var compensators (SVC). On the other hand, the PWM techniques used today to control modern static converters such as high power machine drives, strongly depend on the switching frequency of the power semiconductors. Normally, voltage (or current in dual devices) moves to discrete values, forcing the design of machines with good isolation, and sometimes loads with inductances higher than the required design value. In other words, neither voltage nor current are as expected. This also means harmonic contamination, additional power losses, pulsating torques, and high frequency noise that can affect the controllers. All these reasons have generated intensive research works on the topic of PWM modulation [1]–[4]. More recently, multilevel converters [5]–[8] have permitted having many levels or voltage steps to reduce the THD levels. Multilevel converters offer new solutions for high-power applications, where reliability and performance are very important, enabling reduced harmonic interaction at the network and at the load side. In addition multilevel converter produce lower voltage stress at the power semiconductor switches [8].

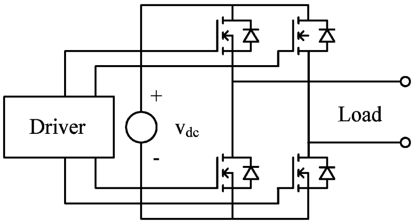

Fig. 1. Three-level module for building multistage converters.

A three-stage converter using "H" power modules, which gives 27 different levels of voltage amplitude is studied [9], [10]. This kind of converters work more like amplitude modulation rather than pulse modulation [11], [12], and hence the converter output is very much cleaner. This way of operation allows having almost perfect currents, and very good voltage waveforms, eliminating most of the undesirable harmonics at the machine side. The output bridges of each converter work at a very low switching frequency, which gives the possibility of working with low speed semiconductors and low switching losses. However, the drawback of this topology is that the complete drive requires nine isolated dc power supplies, where six of them have to be with power reversal capability. This paper shows that these nine dc power supplies can be reduced to only one high power dc source (which manages 80% of the total power), three bi-directional, medium power dc supplies, and three very small unidirectional power supplies. The current and voltage waveforms for a standard 4 kV, 2 MW induction machine are simulated. There are also some experiments with a small laboratory prototype, using a three-stage three-phase converter.

II. BASICS OF MULTISTAGE CONVERTERS

A. Basic Principle

The circuit of Fig. 1 shows the basic topology of one converter used for the implementation of multistage converters. It is based on the simple, four switches converter, used for single phase inverters or for dual converters. These converters are able to produce three levels of voltage in the load: $+v_{dc}$, $-v_{dc}$, and Zero.

The Fig. 2 displays the main components of a three-stage converter which is being analyzed in this work. The figure only

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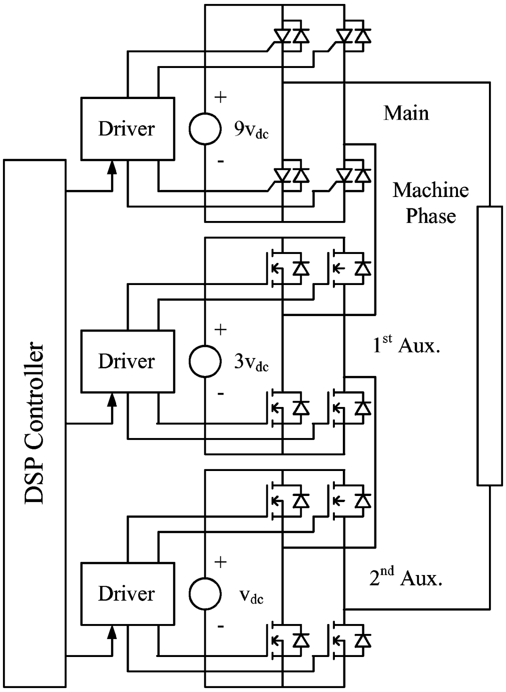

Fig. 2. Main components of the three-stage converter.

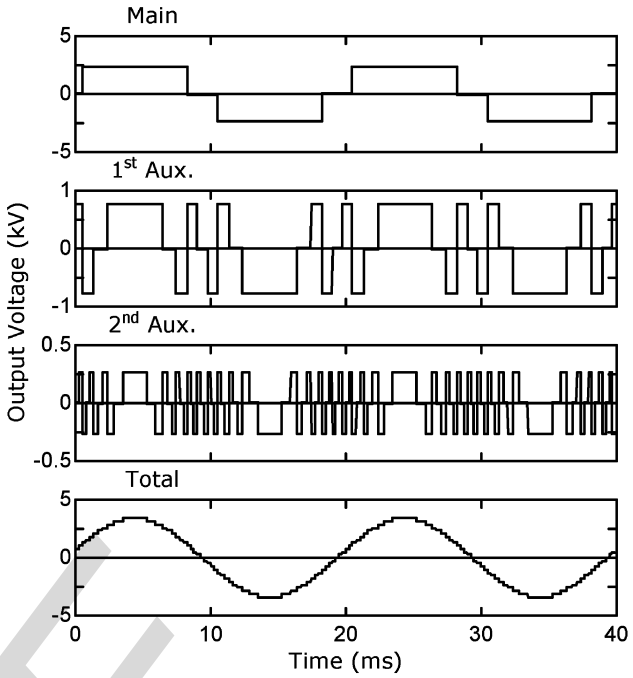

Fig. 3. Output voltage in each stage and total output voltage.

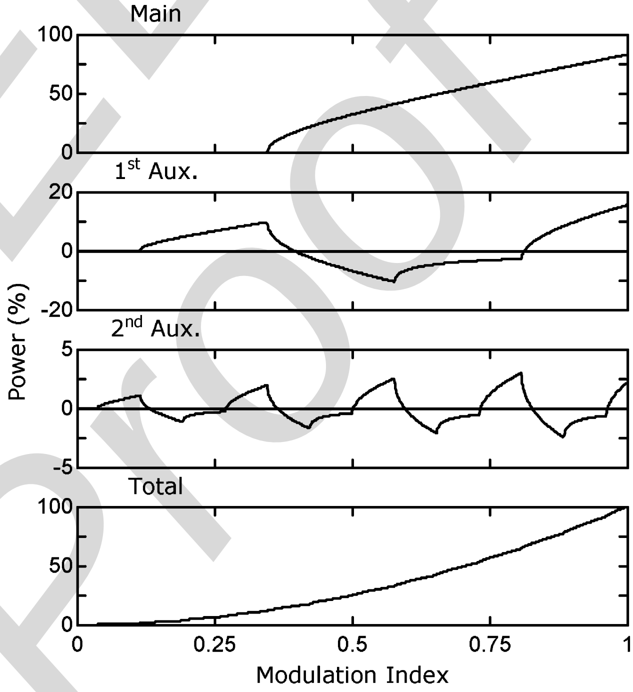

Fig. 4. Active power distribution in a three-stage converter.

shows one of the three phases of the complete system. As can be seen, the dc power supplies of the three converters are isolated, and the dc supplies are scaled with levels of voltage in power of three. The scaling of voltages to the power of three, allows having, with only three converters, 27 (3^3) 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.

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. 3 shows the output voltage of each stage of Fig. 2 and the total voltage applied to the machine. The switching patterns are obtained using round modulation, which selects the output voltage nearest to the reference voltage.

The modulation signal (normalized reference voltage) is multiply by the number of positive levels $(1 + 3 + 9 = 13 \text{ levels})$, and using the round function an index in the range from -13 to $+13$ is obtained. This index is used in a lookup table to select the switching states of each inverter.

B. Power Distribution

One of the good advantages of the strategy described here for multistage converters is that most of the power delivered to the machine comes from the Main Converter. Fig. 4 shows the power distribution in each stage in terms of the modulation index. At nominal output power the Main Converter brings more than the 80% of the total power. The power magnitude of Aux. 1 never surpasses 15% of the total power. The same happens with Aux 2, where the power magnitude never reaches values higher than 3%. The dc power sources required by each stage are proportional to this distribution. This characteristic allows to feed the Auxiliary Converters with low power dc supplies. However, as in some levels of voltage regulation the power goes through the system, requiring bi-directional sources. There are three solutions for this problem: 1) active front-end rectifiers, 2) bi-directional dc-dc power supplies, or 3) passive rectifiers

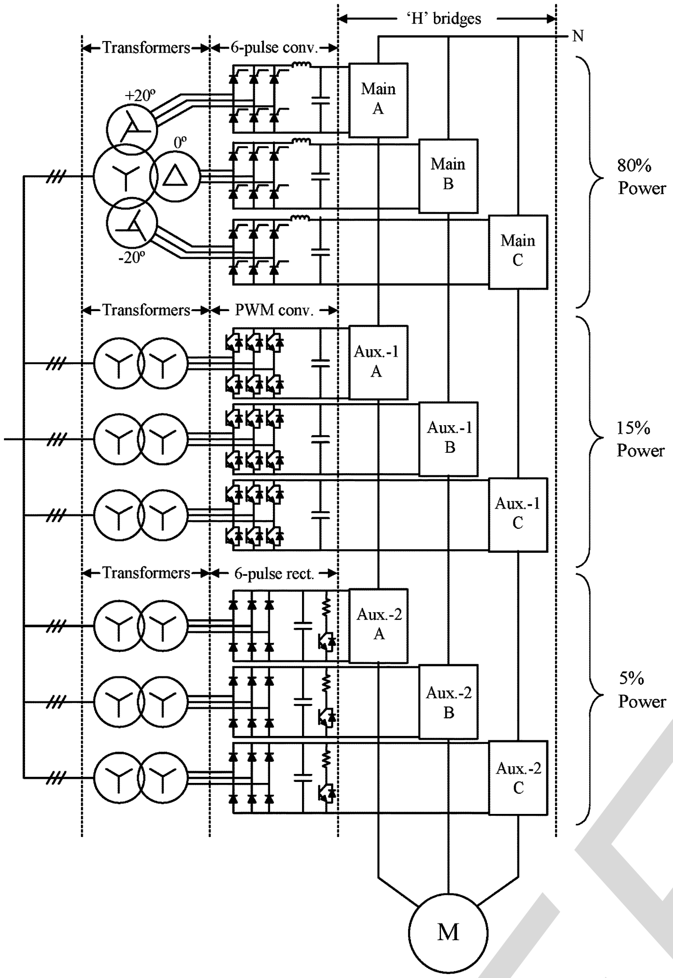

Fig. 5. Multistage converter with Neutral Connected topology (NC topology) for high power drives.

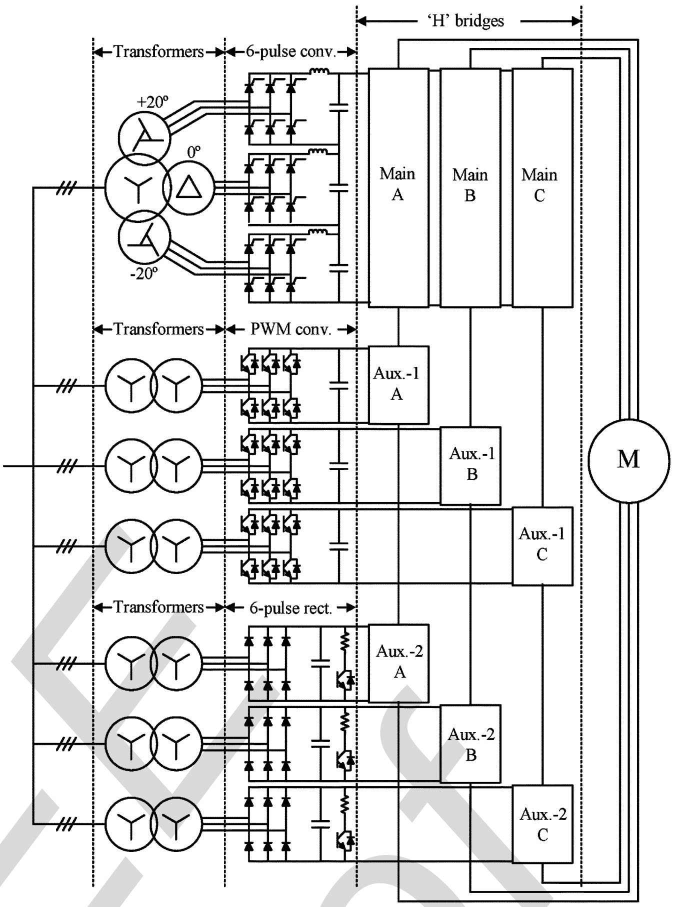

Fig. 6. Multistage converter with Independent Windings topology (IW topology).

with dissipative resistors. In the latter case it will be required to evaluate the power losses.

Another attribute of this configuration, which is possible to see in Fig. 3, is the very low switching frequency of each converter, specially the main, which carries most of the power. Then, the larger the power of the unit, the lower its switching frequency. In the case analyzed here, the main has been implemented with GTOs, and the aux. with IGBTs.

III. INPUT POWER TOPOLOGY

As it was already mentioned, isolated power supplies for each converter are required. In Fig. 5, the electrical schematic of the complete power part including rectifiers and inverters is displayed. The three mains are fed with standard rectifiers, each one in 6-pulse configuration. These rectifiers are isolated from the supply by a four winding transformer, to create three secondary voltage systems, one for each of the three mains, and shifted in $+20^\circ$, 0°, and -20°. With this configuration, a very low harmonic distortion from the mains point of view is obtained [13].

Each one of the first aux. ("Aux. 1" A, B, and C in Fig. 5), needs bidirectional power supplies because at some low voltage operation the power goes from the machine to the mains. To solve this problem, three PWM active rectifiers are used. The advantage of using this type of rectifier at this stage is that they work as a power factor compensator as well as active power filters from the mains point of view, making allowance for almost perfect current waveforms at the supply side.

Finally, the second aux. ("Aux. 2" A, B, and C in Fig. 5), are fed with simple Graetz bridges with dissipative resistors, which are necessary when the machine operates with very low voltage (less than 15%) during starting. However, they can also be implemented with PWM rectifiers like "Aux. 1."

The drawback of the NC topology is that the power rectifiers of the mains need a good filter at the dc link, because each main represents a single-phase load. To avoid this problem, the three mains can be fed in parallel, keeping the transformer configuration with the rectifiers connected in series as shown in Fig. 6. Using this parallel configuration the dc voltage ripple is reduced because the load fed by the main rectifiers is a three-phase load instead of standard single-phase load. The smaller dc voltage ripple improve the quality of output voltage and input current and requires a smaller dc capacitor. However, the three windings of the machine have to be fed independently (no electrical connection between them). This is not uncommon because many machines are built with three independent windings because this characteristics allow to connect the motor in delta or wye connection.

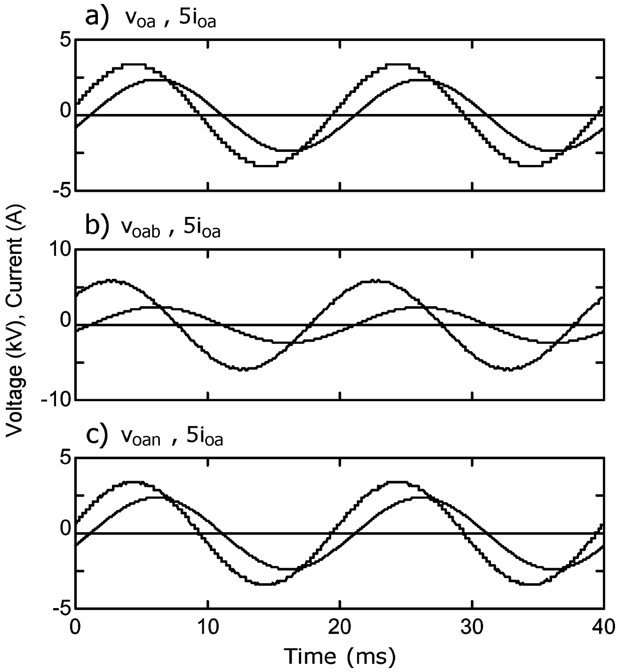

Fig. 7. NC topology (a) converter voltage and output current, (b) phase-to-phase voltage and output current, and (c) phase-to-motor neutral voltage and output current.

IV. Simulated Waveforms

The following simulations were performed using PSIM, a special simulator for power electronics circuits [15]. The machine is a 2 MW, 4 kV induction motor, with $\mathrm{p.f.} = 0.84$. For this simulation the frequency and the slip of the machine have been kept constant. Fig. 7 shows the output voltages and the motor current produced by the three-stage converter with the NC topology. The converter output voltage, the phase-to-phase voltage, the phase-to-motor neutral voltage, and the motor current are displayed. In the case of independent windings topology, the output voltage of the three-stage converter is the same as the phase-voltage of the machine, because the windings are independent and isolated.

The main advantage of IW topology is the reduced ripple in the dc voltage because the current comes from a three-phase load instead of a single-phase load in the NC topology. Fig. 8 shows the dc voltages for both topologies and clearly shows this effect. Also, when the dc voltage has a lower ripple the input current is improved like shows Fig. 9, where the input current of the IW topology is almost sinusoidal.

The output voltage presents a very low Total Harmonic Distortion, but when the modulation index is decreased the distortion grows. Fig. 10 shows the output voltage THD of a three-stage converters in terms of modulation index. The THD is less than 5% at 50% of modulation. It can be noticed that the current remains almost sinusoidal even with 25% voltage amplitude, without the need of PWM modulation.

Interestingly, THD produced by low modulation index (i.e., $\mathrm{m} < 0.25$) has low frequency components like shows Fig. 11. This feature is characteristic of round modulation, instead of PWM modulation where the frequency components are mainly at the switching frequency.

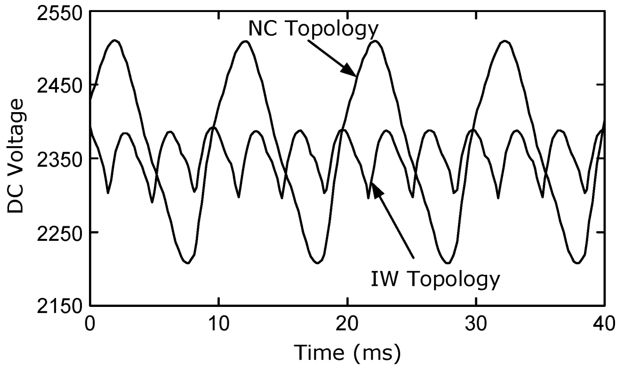

Fig. 8. DC voltages for both topologies.

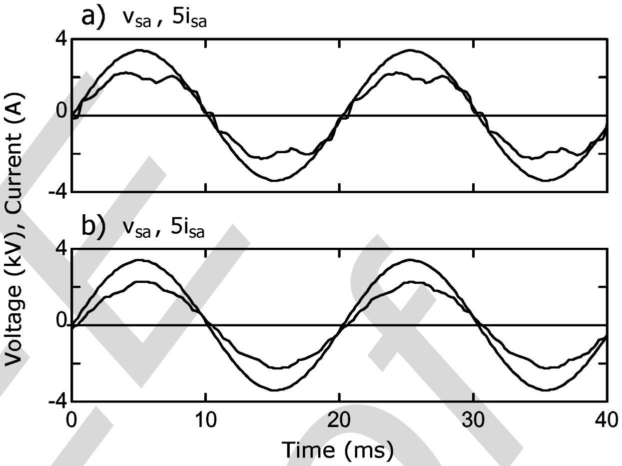

Fig. 9. Input currents for both topologies (a) NC topology and (b) IW topology.

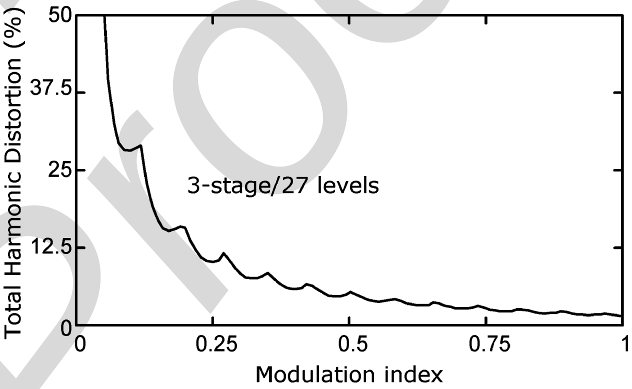

Fig. 10. Output voltage THD in terms of modulation index for three-stage converter.

It is also important to show the power distribution in each stage of the power converter, particularly in some cases where the power is reversed with the voltage variations. Fig. 12 shows the particular case $\mathrm{m} = 0.62$ when both Aux. 1 and Aux. 2 are returning power from the motor to the system. This reason justifies the fact of using active front end rectifiers at the first Aux. level and dissipative rectifiers at the second Aux., otherwise, the power could not be returned to the mains charging the dc capacitors and increasing the dc voltage. These higher dc voltages does not have the power of three relationship reducing the

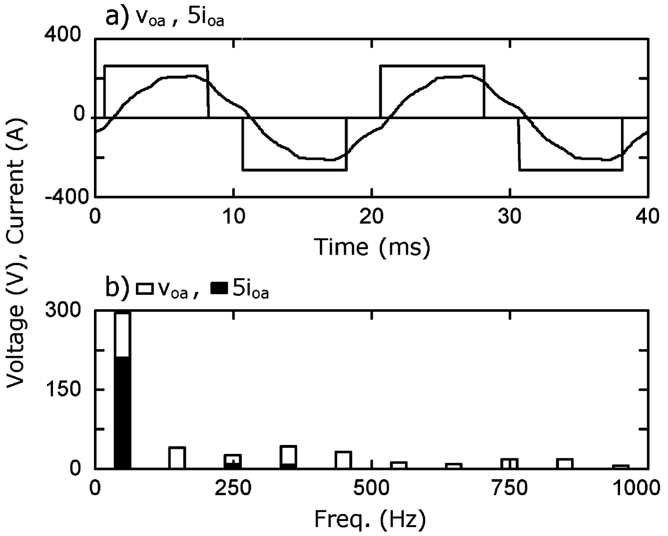

Fig. 11. Machine at 10% of output voltage (a) output voltage and load current waveform and (b) frequency components of output voltage $(\mathrm{THD} = 28\%)$ and load current $(\mathrm{THD} = 5\%)$.

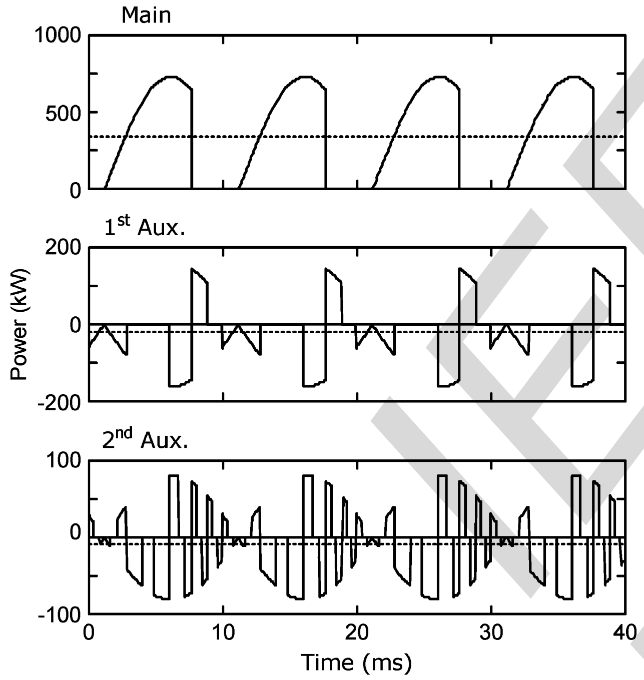

Fig. 12. Power distribution in the three stages of the converter at $\mathrm{m} = 0.62$. (a) Main (mean power 300 kW), (b) Aux. 1 (mean power -25 kW), and (c) Aux. 2 (mean power -10 kW).

output voltage quality and also they can cause damage to the equipment.

V. EXPERIMENTAL RESULTS

An experimental converter prototype feed a 5 kW, 4-pole induction machine load with 0.84 power factor, the phase to neutral voltage is 110 V and the nominal current is 10 A. Fig. 13 shows the output voltage steps waveforms obtained with experimental prototype.

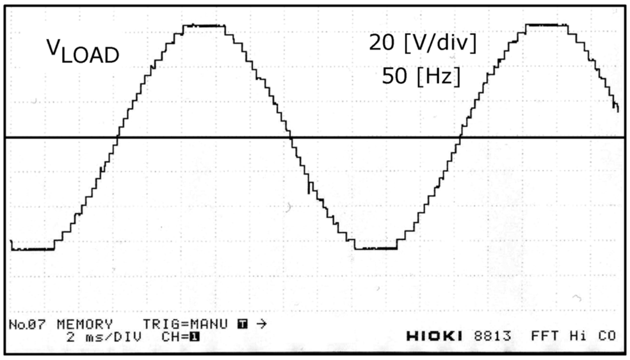

Fig. 13. Voltage steps waveforms in a three-stage converter.

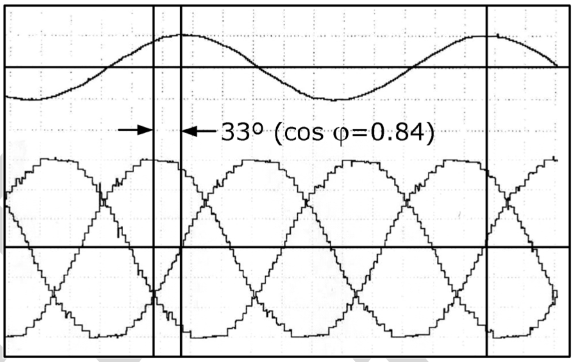

Fig. 14. Single-phase current and three-phase voltages.

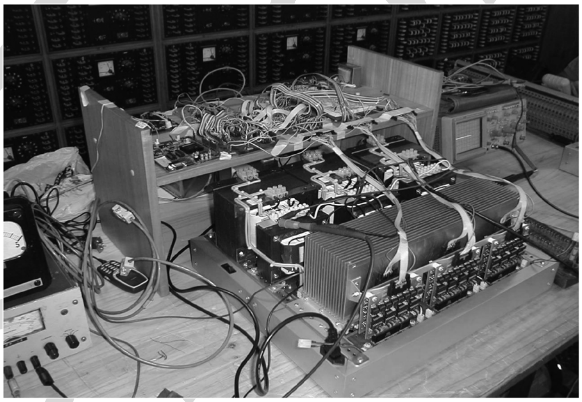

Fig. 15. Three-stage multistage converter prototype.

Fig. 14 shows the voltages of the three phases, and the current in one of them. It is noticed that the current is almost sinusoidal.

The prototype used for the experiments is shown in Fig. 15. It was built using "H" bridges modules of IGBTs. As these modules have their base plate electrically isolated, only one heatsink was required for all the modules of the three phases.

The experimental results justify the research with this kind of converter because, as was shown in Figs. 5 and 6, they are specially suited for very large machine drives, which can be implemented with GTOs or IGCTs at the main level, and with IGBTs at the auxiliary levels. The low distortion voltage at the machine windings contributes also to mitigate EMC/EMI issues related with the commutation of power semiconductors [14] and voltage stress of the winding coils. The apparent complexity of the input transformer and multiple components are not difficult issues to be solved, which in the authors' opinion are well compensated with the better reliability and performance needed for medium and high-power drives.

VI. CONCLUSIONS

A three-stage inverter for high-power machine drive applications, using "H" converters has been analyzed. As this converter generates 27 levels of voltage, the machine current becomes almost perfectly sinusoidal. However, the need of isolated and bidirectional dc power supplies, required for each one of the three stages of the multistage converter, represent the main drawback. The overcome this problem, the paper has proposed three associated solutions: a) passive rectifiers at the Main level (which manages more than 80% of the power), b) active front-end PWM rectifiers at the Aux. 1 level (which manage around 15% of the power and act as power filter and var compensator), and c) passive rectifiers with dissipative power resistors during very low voltage operation at the Aux. 2 level (only 3% of the total power). Some computer simulations were performed and some experiments, with a small three-stage prototype, were displayed.

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