27-Level Converter for Electric Vehicles Using Only one Power Supply

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***Abstract*— The main advantage of asymmetrical multilevel inverters is the optimization of levels with a minimum number of power supplies. However, this optimized multilevel system still needs a large number of isolated and floating DC supplies, which makes these converters complicated to implement in electric vehicles (EVs), because the system will require many independent battery packs. In this paper, a very simple scheme, based on a small and cheap high frequency link (HFL), allows the utilization of only one power supply for the complete multilevel inverter drive, with an inherent regulation of the voltages supplied among the H-bridges. It also allows voltage control with full number of levels if the DC power supply is of variable voltage characteristic. This work is focused on a 27-level asymmetric inverter but the strategy, using only one power supply, can be applied to converters with any number of levels. In particular, an asymmetrical 27-level converter needs nine isolated power supplies and the proposed system reduces these nine sources to only one: the battery car. The topology also permits full regenerative braking working as a three-level converter. The proposed system is intended for application in electric vehicles from power ratings up to 150 kW. Simulations and experimental results show the feasibility to implement this "one-source" multilevel system.**

***Index Terms*— AC Motor drives, Power Conversion, Multilevel Converters, Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs).**

I. INTRODUCTION

Today, cascade multilevel converters have become to be very popular, because they are able to generate voltage waveforms with negligible distortion when compared with conventional inverters based on two or three-level topologies [1-3]. One step ahead was the asymmetrical multilevel converter, which allows the generation of much more levels of voltage with a minimum number of power supplies [4-6]. The increase in the number of voltage levels reduces the Total Harmonic Distortion (THD), voltage and currents of common mode, output filters and switching losses (the main bridges, which carry 80% of total power, works at very low frequency in asymmetrical cascaded multilevel inverters) [6, 7].

Despite this important improvement, these topologies have an important drawback: They need many independent power supplies that must be floating, isolated and balanced. Besides, in some particular levels of voltage, bidirectional power supplies are required, and the same happens when regenerative braking needs to be applied. Other drawback is the direct relations between number of levels and voltage amplitude, producing a loss of quality when the output voltage is reduced. For this reason, costly and complex topologies have to be implemented to get the nine isolated supplies [8, 9]. In applications with constant frequency operation, like power rectifiers, active power filters or flexible AC transmission systems (FACTs), power transformers are used to connect the load, allowing the operation with only one dc supply [10-12]. This solution is not applicable in electric vehicles because all H bridges must be connected in parallel at the same DC supply, and the isolation and voltage scaling problems are solved with multi-winding transformers: one winding for each Aux-Bridge. Moreover, this solution introduces heavy, bulky and complicated transformers, and does not work when variable frequency is required, as the case in electric vehicles (EVs).

An improvement for drive applications has permitted to reduce the number of power supplies using floating capacitors, unidirectional power sources and a special PWM strategy called "Jumping Modulation" [13]. However, it still makes multilevel inverters a complicated solution, because the independent battery packs are only partially reduced (in the case of a 27-level inverters, the nine supplies are reduced to only four).

Other solutions using cascaded multilevel inverters with a single power source and without transformers have been introduced recently [14-16]. However, these solutions use floating capacitors with complex balancing systems and many more semiconductors in relation to the number of levels produced.

The objective of this work is to develop a new DC-link topology for an asymmetrical multilevel inverter, based on a simple High Frequency Link (HFL), which allows using only one power supply (battery pack, fuel cell or other). This single-dc-supply system is especially suitable for EVs, but can also be used for HEVs and industrial machine drives. The system has inherent regulation of the voltages supplied among the H-bridges, so the full number of levels can be produced at any amplitude of voltage, depending only on the singe-dc-supply regulation, which can be controlled with a chopper. This proposed topology does not need floating capacitors or heavy-bulky transformers. The topology also allows full regenerative operation when power supply accepts power reversal (batteries or active front-end rectifiers). During regeneration, the system works as a three-level inverter, but this is not a big drawback because regenerative braking is normally used for short periods.

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II. OPERATION CHARACTERISTICS

The Fig. 1 shows a complete one-phase circuit for a machine drive, using an asymmetrical 27-level inverter based on H-Bridges scaled in power of 3. As can be seen, it needs three independent power supplies per phase, one for each H-Bridge, which means a total of nine power supplies for the complete topology.

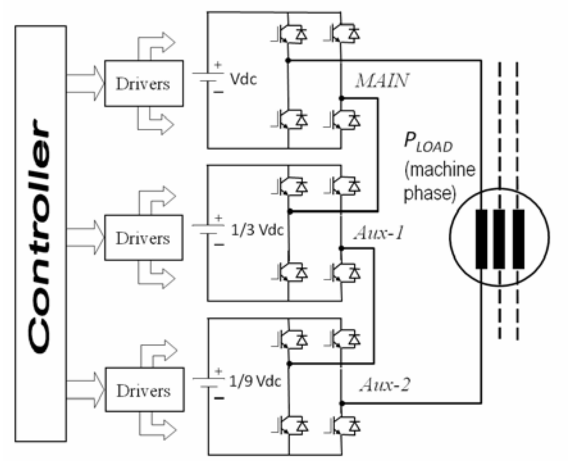

Fig. 1. Main components of the asymmetrical, 27-level drive (one phase).

One advantage of this particular asymmetric converter is that most of the power delivered to the machine comes from the largest H Bridges, called "*MAIN*" bridges. The example of Fig. 2 shows the simulated power distribution in one phase of the 27-level converter, as a function of output voltage. At full power, around 81% of the real power is delivered by the Main converters, but only 16% from the *Aux-1* bridges and approximately 3% of the total power from *Aux-2* bridges.

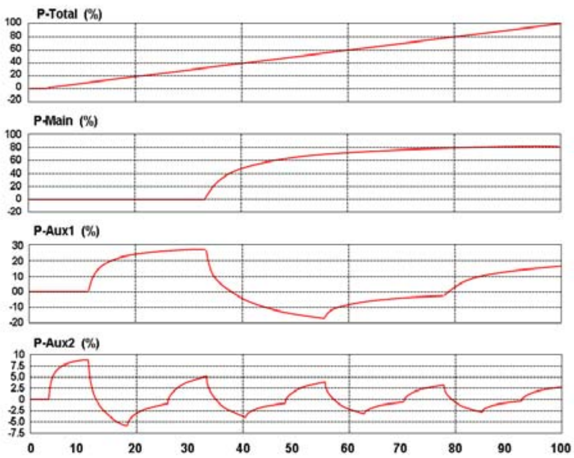

Fig. 2. Power distribution as a function of voltage amplitude.

The best and simplest modulation strategy for this kind of converter, is the Nearest Level Control (NLC) [17], which is being used in this work. The NLC consists on taking the voltage level that is closets of the reference $\left(V_{MAX}^{1}\right)_{REF}$, as shown in Figs. 3 and 4. NLC has two advantages: very low switching frequency and excellent dynamic performance.

The full power per phase delivered for an asymmetrical N-level converter is:

$$P_{LOAD} = \sum_{j=0}^{N}\left(V_{RMS}^{1} \cdot I_{RMS}^{1} \cdot \cos\varphi\right)_{j} = \left(V_{RMS}^{1} \cdot I_{RMS}^{1} \cdot \cos\varphi\right)_{MAIN} + \left(V_{RMS}^{1} \cdot I_{RMS}^{1} \cdot \cos\varphi\right)_{Aux-1} + \left(V_{RMS}^{1} \cdot I_{RMS}^{1} \cdot \cos\varphi\right)_{Aux-2} + \ldots\ldots \quad (1)$$

Where V^{1}_{RMS}, I^{1}_{RMS} and $cos\varphi$ are the fundamentals of voltages, currents and power factor respectively. The term $j=0$ is the *MAIN* converter and $j=N$ correspond to the *Aux-N* converter (the smallest in the chain). As the bridges are in series:

$$\left(I_{RMS}^{1}\right)_{LOAD} = \left(I_{RMS}^{1}\right)_{MAIN} = \left(I_{RMS}^{1}\right)_{Aux-1} = \left(I_{RMS}^{1}\right)_{Aux-2} \quad (2)$$

Besides, $(V^{1}_{RMS})_{MAIN}$, $(V^{1}_{RMS})_{Aux-1}$ and $(V^{1}_{RMS})_{Aux-2}$ are in phase as shown in Fig. 3 and consequently, the power factor is the same for all bridges. For those reasons, the percentage of power distribution is the same as the *RMS* voltage distribution.

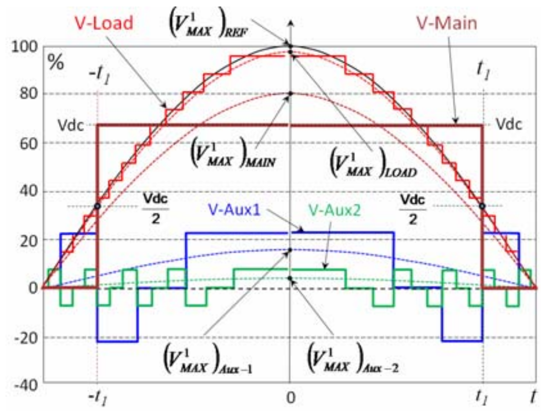

Fig. 3. Voltage waveforms and fundamental voltage at each H-Bridge using the NLC modulation.

From (1) and (2):

$$\left(V_{RMS}^{1}\right)_{LOAD} = \left(V_{RMS}^{1}\right)_{MAIN} + \left(V_{RMS}^{1}\right)_{Aux-1} + \ldots + \left(V_{RMS}^{1}\right)_{Aux-N} \quad (3)$$

or:

$$\left(V_{MAX}^{1}\right)_{LOAD} = \left(V_{MAX}^{1}\right)_{MAIN} + \left(V_{MAX}^{1}\right)_{Aux-1} + \ldots + \left(V_{MAX}^{1}\right)_{Aux-N} \quad (4)$$

As the H-bridges are scaled in power of three, the size of each level is Vdc/3^{N} as shown in Fig. 4.

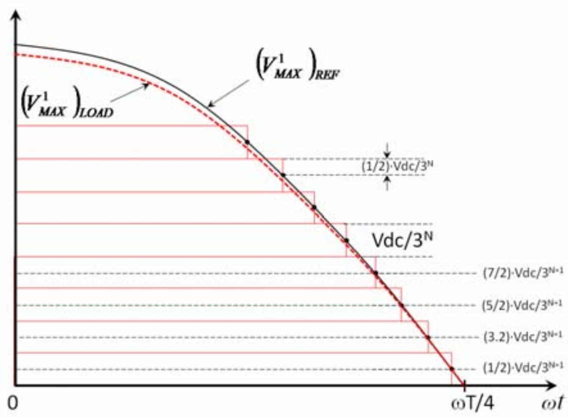

Fig. 4. Size of voltage levels for a multilevel inverter scaled in power of 3.

Using Fourier series decomposition, $\left(V_{MAX}^{1}\right)_{LOAD}$ can be evaluated with the integration of Fig. 4 step by step:

$$(V_{MAX}^{1})_{LOAD} = \frac{8}{\omega T}\cdot\frac{Vdc}{3^{N}}\left(\int_{\omega t=0}^{\omega t=\cos^{-1}\left(\frac{1}{3^{N+1}}\right)}\cos(\omega t)d\omega t + \int_{\omega t=0}^{\omega t=\cos^{-1}\left(\frac{3}{3^{N+1}}\right)}\cos(\omega t)d\omega t + \ldots + \int_{\omega t=0}^{\omega t=\cos^{-1}\left(\frac{2N+1}{3^{N+1}}\right)}\cos(\omega t)d\omega t\right) \quad (5)$$

$$(V_{MAX}^{1})_{LOAD} = \frac{4Vdc}{3^{N}\pi}\sum_{j=0}^{j=\frac{3^{N+1}-1}{2}}\int_{\omega t=0}^{\omega t=\cos^{-1}\left(\frac{2j+1}{3^{N+1}}\right)}\cos(\omega t)d\omega t \quad (6)$$

Eq. (6) allows getting the values of $\left(V_{MAX}^{1}\right)_{LOAD}$ for whatever number of Aux bridges. If the number of Aux bridges is zero (N=0), then the topology becomes a three-level converter:

$$(V_{MAX}^{1})_{LOAD}\Big|^{N=0} = \frac{4Vdc}{\pi}\sum_{j=0}^{j=1}\int_{\omega t=0}^{\omega t=\cos^{-1}\left(\frac{2j+1}{3}\right)}\cos(\omega t)d\omega t = 1.2\cdot Vdc \quad (7)$$

Now, when the converter has one Aux bridge (only *Aux-1* or N=1), it becomes a nine-level device, and from Eq.(6):

$$(V_{MAX}^{1})_{LOAD}\Big|^{N=1} = \frac{4Vdc}{3\pi}\sum_{j=0}^{j=4}\int_{\omega t=0}^{\omega t=\cos^{-1}\left(\frac{2j+1}{9}\right)}\cos(\omega t)d\omega t = 1.44Vdc \quad (8)$$

Finally, if the number of Aux bridges is two (N=2) then it becomes a 27-level inverter, and the value of $\left(V_{MAX}^{1}\right)_{LOAD}$ in terms of Vdc is:

$$(V_{MAX}^{1})_{LOAD}\Big|^{N=2} = \frac{4Vdc}{9\pi}\sum_{j=0}^{j=13}\int_{\omega t=0}^{\omega t=\cos^{-1}\left(\frac{2j+1}{27}\right)}\cos(\omega t)d\omega t = 1.49Vdc \quad (9)$$

Theoretically, If the number of Aux bridges $\rightarrow\infty$:

$$(V_{MAX}^{1})_{LOAD}\Big|^{N\rightarrow\infty} = \frac{4Vdc}{3^{N}\pi}\sum_{j=0}^{j=\infty}\int_{\omega t=0}^{\omega t=\cos^{-1}(0)}\cos(\omega t)d\omega t = 1.5Vdc \quad (10)$$

The particular values of $(V_{MAX}^{1})_{Aux-1}$ and $(V_{MAX}^{1})_{Aux-2}$ can be obtained in the following way:

$$(V_{MAX}^{1})_{Aux-1} = (V_{MAX}^{1})_{LOAD}\Big|^{N=1} - (V_{MAX}^{1})_{LOAD}\Big|^{N=0} = 0.24Vdc \quad (11)$$

$$(V_{MAX}^{1})_{Aux-2} = (V_{MAX}^{1})_{LOAD}\Big|^{N=2} - (V_{MAX}^{1})_{LOAD}\Big|^{N=1} = 0.05Vdc \quad (12)$$

This mean, in terms of $\left(V_{MAX}^{1}\right)_{LOAD}$ for N=2 in Eq. (9):

$$\frac{(V_{MAX}^{1})_{MAIN}}{(V_{MAX}^{1})_{LOAD}} = \frac{(V_{MAX}^{1})_{LOAD}\Big|^{N=0}}{(V_{MAX}^{1})_{LOAD}\Big|^{N=2}} = \frac{1.2}{1.49} = 0.81 \quad (13)$$

$$\frac{(V_{MAX}^{1})_{Aux-1}}{(V_{MAX}^{1})_{LOAD}} = \frac{0.24}{1.49} = 0.16 \quad (14)$$

$$\frac{(V_{MAX}^{1})_{Aux-2}}{(V_{MAX}^{1})_{LOAD}} = \frac{0.05}{1.49} = 0.03 \quad (15)$$

Then, for an asymmetrical three-bridge, 27-level converter, 81 % of the total power comes from the *MAIN* converter. It is important to realize that the minimum amount of power coming from the *MAIN* to the load is when in $N\rightarrow\infty$:

$$\frac{\left(V_{MAX}^{1}\right)_{MAIN}}{\left(V_{MAX}^{1}\right)_{LOAD}\Big|^{N\rightarrow\infty}} = \frac{\left(V_{MAX}^{1}\right)_{LOAD}\Big|^{N=0}}{\left(V_{MAX}^{1}\right)_{LOAD}\Big|^{N\rightarrow\infty}} = \frac{1.2\cdot Vdc}{1.5\cdot Vdc} = 0.8 \quad (16)$$

As the MAIN bridges handle at list 80% of the full power, the total power delivered from all the Aux Bridges will never go larger than 20 %. This result permits the implementation of the proposed topology: a small and cheap high frequency link (HFL), to feed all the Aux bridges. The HFL uses a square voltage waveform H-bridge, with a small, low weight and low cost isolated transformer. The HFL allows the reduction of floating DC supplies from three per phase to only one per phase. The "one per phase" reduction means three isolated sources for the complete system. However, with a small change in the wiring connection of the traction motor, only one DC supply will be required for the complete system. Each of the three phases of the traction motor (induction, PMSM or BLDC machine), are connected separately as shown in Fig. 5. With this solution, the three MAIN bridges can be connected in parallel to just one DC supply. This solution matches perfectly with the requirement for traction applications: only one power supply (just one battery pack).

To keep the full number of levels for all output voltage amplitudes, a DC voltage controller (Chopper) is included in the topology. However, the system also works without the Chopper, but in this case the NLC control produces a reduction of levels and consequently a bad THD. Another solution to avoid the Chopper, keeping a good THD, is changing the PWM modulation on the H-Bridges, but due to the great increase of the switching frecuancy, the efficiency of the converter will diminish.

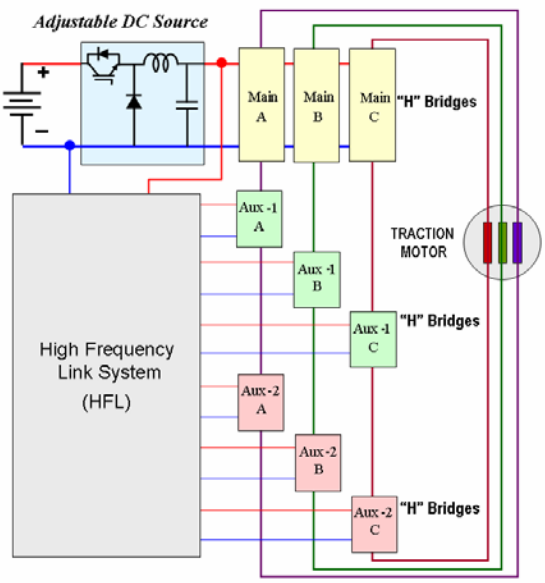

Fig. 5. Proposed topology using only one power supply

All the Aux converters (six in total) are fed from the proposed high frequency link. The high frequency link consists on a simple square wave generator, implemented with an H-bridge working at high frequency (10-100 kHz) and a small ferrite transformer to isolate the outputs of each Aux Converter. The high frequency operation is quite important because it allows an important reduction in size and weight of components, mainly the power transformer. This square-wave H-bridge is fed from the Adjustable DC Source shown in Fig. 5 and the voltage generated is connected to the primary of the transformer, which has many secondary windings. In the case of the 27-level inverter, the transformer has six of these secondary windings, three of them with turn ratios 9:3 and three with ratios 9:1. Then, six square wave voltages with reduced amplitude are generated. Each one of these high frequency voltages are rectified using simple diode bridges. The advantage of using diode rectifiers is that they do not need to be controlled. They also will keep the relation 9:3:1 at the corresponding dc-link voltages, avoiding additional voltage distortion when the Adjustable DC Source is modified. Then, if for example this voltage changes 30%, all H-bridges of the multilevel inverter will change 30% keeping the voltage at the traction motor undistorted.

III. HIGH FREQUENCY DC LINK

The number of turns of secondary and tertiary windings is scaled in power of three with respect to the DC link voltage of the MAIN converters. These windings generate square waves that are rectified to feed each one of the Aux Bridges independently, keeping them isolated. In this way, all H-Bridges are fed from the Adjustable DC Supply and the output voltage is modified changing the voltage of this DC supply. The Fig. 6 shows the high frequency link.

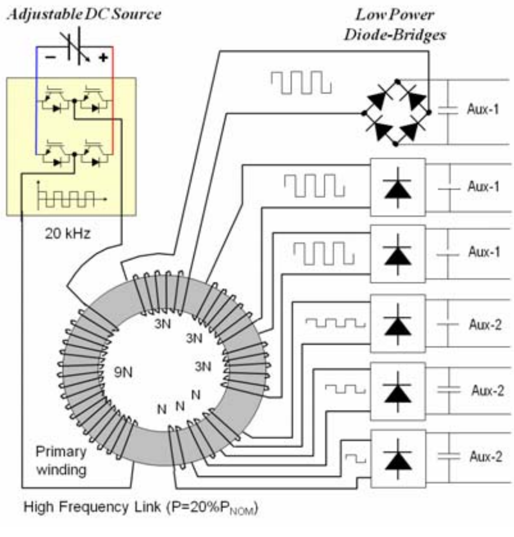

Fig. 6. The high frequency link (HFL).

When the DC Supply is constant and then cannot be adjusted, output voltage must be controlled changing the switching pattern on the transistors of the H-Bridges. In this case, at some particular levels of voltage, the power at some of the Aux-Bridges can become negative. As the Low Power Rectifiers connected at the Aux- Bridges are unidirectional, their DC capacitors will need to absorb small amounts of energy coming from the motor during those periods. For example, at 55% output power, the Aux-1 Bridge has 15% negative power as shown in Fig. 2. If this amount of energy is too large, the capacitor voltage can increase to undesired voltages, and in this case, a special PWM strategy, based on jumping those negative levels is applied [13]. This operation is only necessary when the DC supply cannot be adjusted.

The number of turns of secondary and tertiary windings is scaled in power of three with respect to the DC link voltage of the Main converters. As the diode bridges are unidirectional, the DC capacitors will need to absorb small amounts of energy during short periods, but only when the DC supply is not adjustable and for specific output voltage levels as shown in Fig. 2. If this amount of energy is too large, the capacitor voltage can increase to undesired voltages, and in this case, a special PWM strategy, based on jumping those negative levels is applied [13].

Transformer Design.

As the transformer work with square wave:

$$\therefore \quad V_{RMS} = 4 \cdot f \cdot N \cdot A \cdot B_{MAX} \tag{20}$$

Where f is the switching frequency, N the number of turns, A de area of the core and B_{MAX} de flux density.

As the HFL works at very high frequency, its size and weight becomes very small. For example, in a car with 100 kW traction motor, a 20 kW HFL is required (20% of total power). If the supply voltage is 300 Vdc, the RMS value of the square voltage (at the primary winding) is also 300 V. The HFL has to supply from the battery 60,7 Amps to compensate the current of all the Aux bridges at full power (18.2 kW for a 27-level converter as was shown in Eq. 3). The Aux-1 bridges will take 5.33 kW each and the Aux-2, 1 kW each. As voltage at Aux-1 bridges is 100 Volts, their currents will be 53.33 Amps. On the other hand, the Aux-2 bridges (33.3 Vdc) will take 30 Amps. Working at a frequency of 20 kHz, with a core transformer of 9 cm^2 (3x3 cm), and with a flux density of 0.2 Tesla, the number of turns required by the primary of the toroidal transformer is:

$$N = \frac{V_{RMS}}{4 \cdot f \cdot A \cdot B_{MAX}} = \frac{300}{4 \cdot 20 \cdot 10^{3} \cdot 9 \cdot 10^{-4} \cdot 0.2} = 21 \tag{18}$$

Then the primary must have at least 21 turns. The design should consider 27 turns to satisfy the voltages scaled in power of three. With 27 turns in the primary, only 9 turns for each Aux-1 and just 3 turns for each Aux 2 are required. Assuming 18.2 kW at 300 Vdc means 60.7 Adc at the primary winding. For this current, a 20 mm^2 cooper wire is enough. For the windings of Aux-1 and Aux-2, 18 and 10 mm^2 are required respectively. In total, 27 turns of 20 mm^2 for the primary winding, 27 turns of 18 mm^2 for all Aux-1 windings and 9 turns of 10 mm^2 for all Aux-2 Bridges (9 turns for each Aux-1 and 3 turns for each Aux-2). Assuming a toroidal transformer with a hole 5 times the total area required for all the windings, the hole should have an area of (27x20+27x18+9x10)x5 =5600 mm^2 (a toroid of 8 cms internal diameter is enough). The Fig. 8 shows the size (in cm) of the high frequency transformer for a 100 kW traction system.

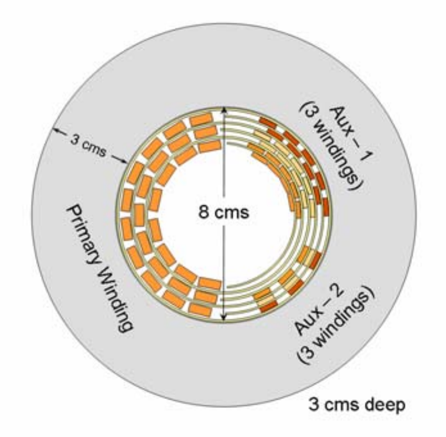

Fig. 8. Toroidal Transformer for 100-kW converter.

IV. Regenerative Braking

The proposed system regenerates using a three level topology because the Aux-1 and Aux-2 bridges are fed by diode bridges. To have 27-level operation for regenerative braking, the system needs to be more complicated and each one of the diode bridges of Fig. 6 must be replaced by active rectifiers (six H-Bridge modules). That solution increases complexity and cost because these active rectifiers need to be controlled by means of software an additional hardware. This extra hardware is required for switching 24 new transistors with the corresponding wirings and floating supplies (or 24 optic fibers). This more complicated topology does not improve efficiency, because diodes are more efficient than those reversible full transistor H bridges. Besides, the simple-diode solution does not affect the regeneration process, because Aux-bridges are bypassed by switching them to zero-volt operation, as shown in Fig 9.

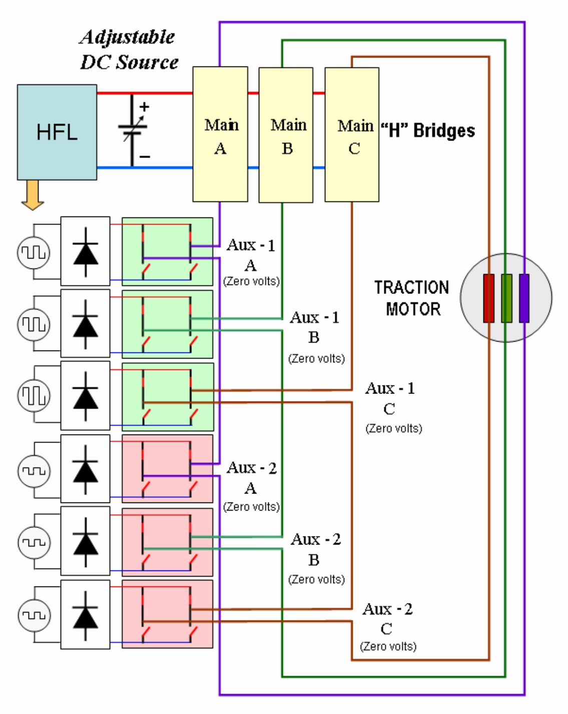

Fig. 9. Three-level topology for regenerative braking

V. Simulations

To see the performance of the proposed system, some simulations were performed using PSIM simulator. One particular characteristics of the proposed high-frequency link is that all the nine DC sources depend on the Adjustable *DC* Source. When this voltage is modified, the output rms voltage is also modified but is not distorted because the nine power supplies change proportionally. With this characteristic, the sinusoidal waveform that feeds the traction motor remains intact, no matter how much the DC Source changes. Variable DC voltage allows using the NLC strategy, which gives the smallest voltage distortion (only 3% THD). In fact, if variable DC voltage is used, all the H-bridges can be kept with a fixed PWM pattern, stored in firmware mode. Fig.10 shows the voltage waveform using NLC under battery voltage variations, showing always the full number of levels.

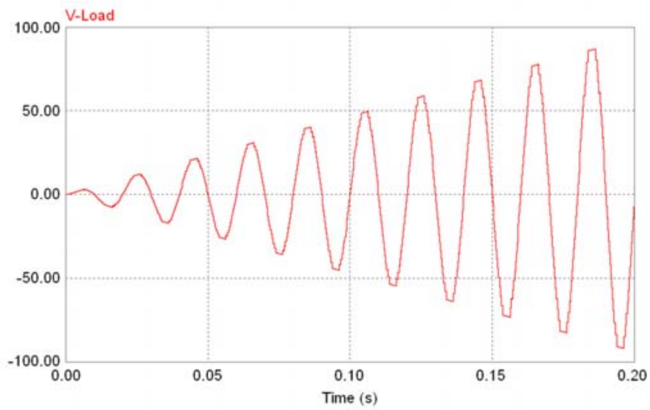

Fig. 10. Voltage variation at machine windings

Figure 11 shows the application of PWM using the "Jumping Modulation" developed in [13] to control the output voltage when the dc supply is constant. When output voltage is modified by the PWM, in some particular levels the power of Aux bridges could become negative, situation that must be avoided. In this case, the "Jumping Modulation" is applied to jump the corresponding level, keeping it at zero volts and applying PWM on the upper level bridges.

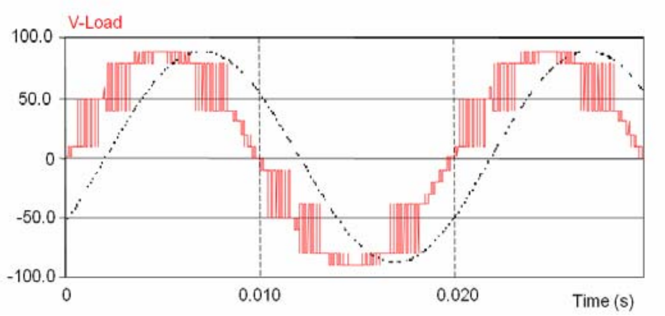

Fig. 11. "Jumping Modulation" to avoid negative power at Aux.Bridges.

VI. Experimental Results

To test the overall performance of the system, a 3 kW experimental prototype was assembled. Figure 12 shows a picture of the prototype and a detail of the high-frequency toroidal transformer, which works at 20 kHz.

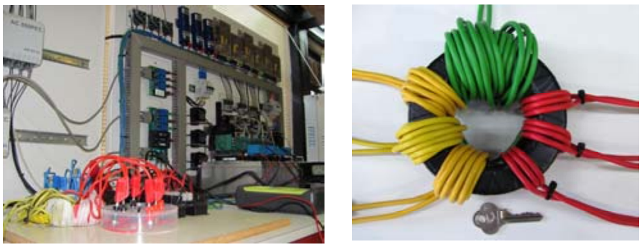

Fig. 12. Photograph of the prototype and the high-frequency transformer.

Figure 13 shows the voltage waveform applied to the load (small squirrel-cage induction motor). As can be seen, the waveforms are quite clean (NLC Modulation) and the THD is only 3%.

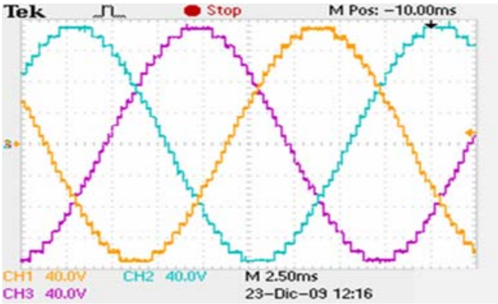

Fig. 13. Voltage waveforms at the machine terminals with NLC

Figure 14 shows that the 27 levels remain without distortion, when the *DC* voltage is adjustable with a Chopper like the one showed in Fig. 5. The PWM used for the asymmetric inverter is the NLC strategy [17], which does not need to be modified (fixed PWM pattern). All the output amplitudes to the traction motor are controlled with just one IGBT used in the chopper. Note that this chopper does not need the typical regenerative second transistor, because regeneration is controlled by the *MAIN* Bridges.

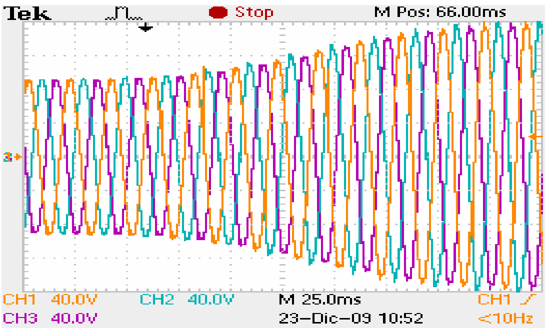

Fig. 14. Output voltage control using a variable *DC* supply

When regenerative braking is applied, the multilevel inverter works as a three-level converter and the *DC* link voltage goes up until it reaches the battery voltage. At this moment, the diode D_R of Fig 5 begins to conduct, returning power to the battery. Fig. 15 shows the transition from motor operation (27-level) to regenerative braking operation (3-level). The electric vehicle being implemented will not behave like Fig. 15, because acceleration pedal and brake pedal are completely independent. This oscillogram is just for showing the transition from motor to generator.

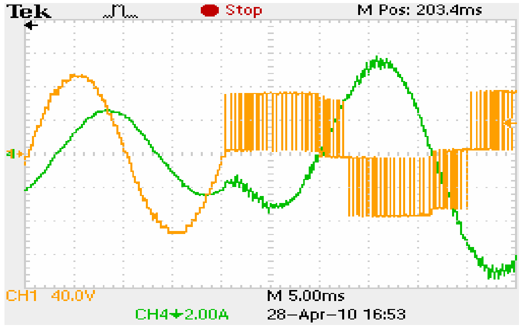

Fig. 15. Transition from motor operation to regenerative operation

If DC voltage variation is not possible, then different PWM control strategies for the output voltage need to be applied. Figure 16 shows a sequence of waveforms using "Jumping Modulation" directly applied to the H-Bridges. The first oscillogram shows the waveforms with almost full output voltage (around 150 Volts peak with all 27 levels). The second one shows an output voltage of around 120 Volts peak. This voltage represents 80% of full voltage, and for this reason the smallest level (Aux-2) must be jumped to avoid regenerative voltage at Aux-2 [13]. Finally, the third oscilogram shows the output at 30% full voltage. With this output, the main converter remains off (only Aux-1 and Aux-2 give power) and the converter works at a 9-level inverter. As can be seen, the control of AC voltage at constant DC voltage changes the number of levels at the output and consequently the THD of voltage increases.

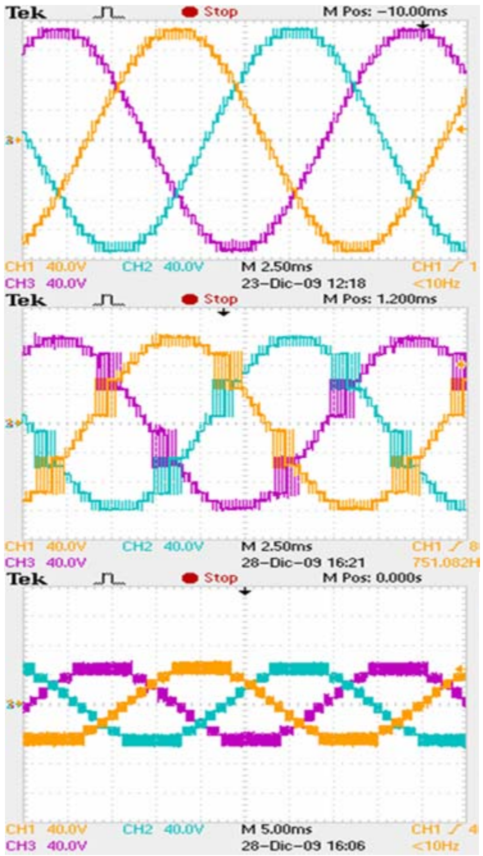

Fig. 16. Output voltage control using PWM and constant dc supply

VI. CONCLUSIONS

An asymmetric cascaded multilevel inverter topology, based on a small and cheap high frequency link (HFL) was proposed, implemented and proved. The proposed solution allows reducing the large number of power supplies required for these inverters to only one, allowing their application in electric vehicles. A 27-level, 3 kW prototype, using NLC modulation control, was implemented to demonstrate some of its advantages: excellent voltage waveforms (3% THD voltage) and hence almost perfect current waveforms. The NLC control increases the efficiency of the inverter because MAIN converters, which manage more than 80% of total power, works at fundamental frequency instead of 10 to 20 kHz, which are normal switching frequencies in two or three-level inverters. Only the HFL works at those frequencies, but it switches only four transistors and represents less than 20% of the full power. Experimental results show the feasibility to implement large inverters for application in electric vehicles from power ratings up to 150 kW. The HFL solution can also be used for many other purposes, as machine drives for industry applications, or high power active-front-end rectifiers. If variable DC source is adjusted using a chopper, only one transistor needs to be controlled to drive the traction motor. For regenerative braking, only MAIN Bridges need to be controlled (three-level operation). With the solution proposed, multilevel inverters become a real solution for electric vehicles and for hybrid electric vehicles applications.

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