Asymmetrical Multilevel Inverter for Traction Drives Using Only One DC 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 the full number of levels if the dc source is of a variable voltage characteristic. This paper 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 EVs 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, electric vehicles (EVs), hybrid EVs (HEVs), multilevel converters, power conversion.

I. INTRODUCTION

TODAY, cascade multilevel converters have become 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 many 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), the common-mode voltages, the output filters, and the switching losses (the main bridges, which carry 80% of the total power, work at a 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. In addition, in some particular levels of voltage, bidirectional power supplies are required, and the same happens when regenerative braking needs to be applied. Another drawback is the direct relation between the number of levels and the voltage amplitude, which produce 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, such as power rectifiers, active power filters, or flexible ac transmission systems, output power transformers are used to connect the load, allowing operation with only one dc supply [10]–[12]. However, this solution is not applicable in electric vehicles (EVs) because all H-bridges must be connected in parallel at the same dc supply, and the isolation and voltage scaling problems are solved with multiwinding transformers: one winding for each auxiliary (Aux) bridge. Moreover, this solution introduces heavy, bulky, and complicated transformers and does not work when a variable frequency is required, as is the case with EV or hybrid EVs (HEVs).

An improvement for drive applications has permitted reducing the number of power supplies using floating capacitors, unidirectional power sources, and a special pulsewidth modulation (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 paper 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 others). This single-dc-supply system is particularly suitable for EVs but can also be used for HEVs and industrial machine drives. The system has an inherent regulation of the voltages supplied among the H-bridges; thus, the full number of levels can be produced at any amplitude of voltage, depending only on the single-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 the 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...
Fig. 1. Main components of the asymmetrical 27-level inverter (one phase).

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

drawback because regenerative braking is normally used for short periods.

II. OPERATIONS CHARACTERISTICS

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, i.e., one for each H-bridge, which means a total of nine power supplies for the complete topology.

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 in 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 the Aux-2 bridges.

The best and simplest modulation strategy for this kind of converter is the nearest level control (NLC) [17], which is being used in this paper. The NLC consists on taking the voltage level that is closest to the reference, as shown in Figs. 3 and 4. The NLC has two advantages, i.e., very low switching frequency and excellent dynamic performance.

The full power per phase delivered for an asymmetrical converter is

\[
P_{\text{LOAD}} = \sum_{j=0}^{N} (V_{1\text{RMS}}^1 \cdot I_{1\text{RMS}} \cdot \cos \varphi)_j
\]

\[
= (V_{1\text{RMS}}^1 \cdot I_{1\text{RMS}} \cdot \cos \varphi)_{\text{MAIN}} + (V_{1\text{RMS}}^1 \cdot I_{1\text{RMS}} \cdot \cos \varphi)_{\text{Aux-1}} + (V_{1\text{RMS}}^1 \cdot I_{1\text{RMS}} \cdot \cos \varphi)_{\text{Aux-2}} + \cdots
\]

(1)

where \( N \) is the number of auxiliary bridges, and \( V_{1\text{RMS}}^1 \), \( I_{1\text{RMS}} \), and \( \cos \varphi \) are the fundamentals of voltage, current, and power factor, respectively. The term \( j = 0 \) represents the MAIN converter, and \( j = N \) corresponds to the Aux-\( N \) converter (the smallest in the chain). As all the bridges are in series

\[
(I_{\text{RMS}})_{\text{LOAD}} = (I_{\text{RMS}})_{\text{MAIN}} = (I_{\text{RMS}})_{\text{Aux-1}} = (I_{\text{RMS}})_{\text{Aux-2}}.
\]

(2)

In addition, \( (V_{\text{RMS}})_{\text{MAIN}}, (V_{\text{RMS}})_{\text{Aux-1}}, \) and \( (V_{\text{RMS}})_{\text{Aux-2}} \) 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.

From (1) and (2)
\[
(V_{\text{RMS}})^{\text{LOAD}} = (V_{\text{RMS}})^{\text{MAIN}} + (V_{\text{RMS}})^{\text{Aux}-1} + \cdots + (V_{\text{RMS}})^{\text{Aux}-N}
\]

or
\[
(V_{\text{MAX}})^{\text{LOAD}} = (V_{\text{MAX}})^{\text{MAIN}} + (V_{\text{MAX}})^{\text{Aux}-1} + \cdots + (V_{\text{MAX}})^{\text{Aux}-N}
\]

As the H-bridges are scaled in power of 3, the size of each level is \(V_{\text{dc}}/3^N\), as shown in Fig. 4.

Using Fourier series decomposition, it can be evaluated with the integration of Fig. 4 step by step, i.e.,
\[
(V_{\text{MAX}})^{\text{LOAD}} = \frac{8}{\omega T} \cdot \frac{V_{\text{dc}}}{3^N} \left(\frac{\omega t = \cos^{-1}\left(\frac{1}{3^N}\right)}{\omega t = 0} \cos(\omega t) d\omega \right)
\]

\[
+ \frac{\omega t = \cos^{-1}\left(\frac{2}{3^N}\right)}{\omega t = 0} \cos(\omega t) d\omega + \cdots
\]

\[
+ \frac{\omega t = \cos^{-1}\left(\frac{2N+1}{3^N}\right)}{\omega t = 0} \cos(\omega t) d\omega.
\]

Equation (6) allows getting the values of \((V_{\text{MAX}})^{\text{LOAD}}\) for a given number of Aux bridges. If the number of Aux bridges is zero \((N = 0)\), then the topology becomes a three-level converter, i.e.,
\[
(V_{\text{MAX}})^{\text{LOAD}}|_{N=0} = \frac{4V_{\text{dc}}}{\pi} \sum_{j=0}^{j=2^{N+1}-1} \int_{\omega t = 0}^{\omega t = \cos^{-1}\left(\frac{2j+1}{3^N}\right)} \cos(\omega t) d\omega.
\]

Finally, if the number of Aux bridges is two \((N = 2)\), then it becomes a 27-level inverter, and the value of \((V_{\text{MAX}})^{\text{LOAD}}\) in terms of \(V_{\text{dc}}\) is
\[
(V_{\text{MAX}})^{\text{LOAD}}|_{N=2} = \frac{4V_{\text{dc}}}{9\pi} \sum_{j=0}^{j=13} \int_{\omega t = 0}^{\omega t = \cos^{-1}\left(\frac{2j+1}{3^N}\right)} \cos(\omega t) d\omega = 1.49V_{\text{dc}}.
\]

Theoretically, if the number of Aux bridges \(\to \infty\)
\[
(V_{\text{MAX}})^{\text{LOAD}}|_{N=\infty} = \frac{4V_{\text{dc}}}{3N\pi} \sum_{j=0}^{j=\infty} \int_{\omega t = 0}^{\omega t = \cos^{-1}(0)} \cos(\omega t) d\omega = 1.5V_{\text{dc}}.
\]

The particular values of \((V_{\text{MAX}})^{\text{ Aux}-1}\) and \((V_{\text{MAX}})^{\text{ Aux}-2}\) can be obtained in the following way:
\[
(V_{\text{MAX}})^{\text{ Aux}-1} = (V_{\text{MAX}})^{\text{ LOAD}}|_{N=1} - (V_{\text{MAX}})^{\text{ LOAD}}|_{N=0} = 0.24V_{\text{dc}}
\]

\[
(V_{\text{MAX}})^{\text{ Aux}-2} = (V_{\text{MAX}})^{\text{ LOAD}}|_{N=2} - (V_{\text{MAX}})^{\text{ LOAD}}|_{N=1} = 0.05V_{\text{dc}}.
\]

This means, in terms of \((V_{\text{MAX}})^{\text{ LOAD}}\) for \(N = 2\) in (9)
\[
(V_{\text{MAX}})^{\text{ MAIN}} = (V_{\text{MAX}})^{\text{ LOAD}}|_{N=0} = \frac{1.2}{1.49} = 0.81
\]

\[
(V_{\text{MAX}})^{\text{ Aux}-1} = \frac{0.24}{1.49} = 0.16
\]

\[
(V_{\text{MAX}})^{\text{ Aux}-2} = \frac{0.05}{1.49} = 0.03.
\]

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 \(N \to \infty\)
\[
(V_{\text{MAX}})^{\text{ MAIN}}|_{N=\infty} = \frac{(V_{\text{MAX}})^{\text{ LOAD}}|_{N=0}}{(V_{\text{MAX}})^{\text{ LOAD}}|_{N=\infty}} = \frac{1.2 \cdot V_{\text{dc}}}{1.5 \cdot V_{\text{dc}}} = 0.8.
\]

As the MAIN bridges handle at least 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, i.e., a small and cheap HFL, to feed all the Aux bridges. The HFL uses a square voltage waveform H-bridge, with a small low-weight low-cost isolated transformer. The HFL allows the reduction of floating dc supplies from three per phase to 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, permanent-magnet synchronous motor, or brushless dc machine) is separately connected, as shown in Fig. 5. With this solution, the three MAIN bridges can be connected in parallel to just one dc supply. This solution perfectly matches 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 using direct modulation on the H-bridges, but in this case, the NLC produces a reduction of levels and, consequently, a bad THD. Another solution to avoid the chopper, keeping a good THD, is changing the PWM on the H-bridges, but due to the great increase of the switching frequency, the efficiency of the converter will diminish.

All the Aux converters (six in total) are fed from the proposed HFL. The HFL consists of a simple square-wave generator, implemented with an H-bridge working at a 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 ferrite 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 of these high-frequency voltages is rectified using simple diode bridges. The advantage of using diode rectifiers is that they do not need to be controlled. They will also 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 by 30%, all H-bridges of the multilevel inverter will change by 30%, keeping the voltage at the traction motor undistorted.

III. HIGH-FREQUENCY DC LINK

Fig. 6 shows the HFL that feeds the Aux converters. As can be seen, the circuit is quite simple, because it only needs a high-frequency H-bridge rated at 20% full drive power, one multiwinding ferrite transformer, and some bridge rectifiers made with simple fast recovery diodes. The H-bridge only needs to generate a square voltage waveform, and hence, no control is required for its operation.

The number of turns of secondary and tertiary windings is scaled in power of 3 with respect to the dc-link voltage of the MAIN converters. These windings generate square waves that are rectified to feed each of the Aux bridges independently, keeping them isolated. This way, all H-bridges are fed from the adjustable dc supply, and the output voltage is modified by changing the voltage of this dc supply.

When the dc supply is constant and then cannot be adjusted, the output voltage must be controlled by 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.

A. Transformer Design

As the transformer work with a square wave, it needs a different design. To generate a square-wave voltage, the flux must be a triangular function, as shown in Fig. 7. The slope of the triangular wave defines the amplitude of the voltage.

According to Fig. 7

\[
\varphi(t) = \begin{cases} 
\frac{\varphi_{\text{MAX}}}{T/4} \cdot (t - \frac{T}{2}), & \text{if } t = \left(0, \frac{T}{2}\right) \\
-\frac{\varphi_{\text{MAX}}}{T/4} \cdot (t - \frac{3T}{4}), & \text{if } t = \left(\frac{T}{2}, T\right)
\end{cases}
\]

\[
v(t) = N \cdot \frac{d\varphi}{dt}
\]

\[
= \begin{cases} 
N \cdot \frac{\varphi_{\text{MAX}}}{T/4} = V_{\text{MAX}}, & \text{if } t = \left(0, \frac{T}{2}\right) \\
-N \cdot \frac{\varphi_{\text{MAX}}}{T/4} = -V_{\text{MAX}}, & \text{if } t = \left(\frac{T}{2}, T\right)
\end{cases}
\]

\[
V_{\text{RMS}} = \sqrt{\frac{1}{T} \left[ \int_{0}^{T/2} V_{\text{MAX}}^2 \, dt + \int_{T/2}^{T} -V_{\text{MAX}}^2 \, dt \right]}
\]

\[
= V_{\text{MAX}} \cdot N \cdot \frac{\varphi_{\text{MAX}}}{T/4} = 4 \cdot f \cdot N \cdot \varphi_{\text{MAX}}
\]

\[
\therefore \quad V_{\text{RMS}} = 4 \cdot f \cdot N \cdot A \cdot B_{\text{MAX}}
\]

where \( f \) is the switching frequency, \( N \) is the number of turns, \( A \) is the area of the core, and \( B_{\text{MAX}} \) is the flux density.

As the HFL works at a very high frequency, its size and weight becomes very small. For example, in a car with a 100-kW traction motor, a 19-kW HFL is required [19% of the total power according to (14) and (15)]. If the maximum voltage at the adjustable dc source of Fig. 5 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 63.3 A to compensate the current of all the Aux bridges at full power. The Aux-1 bridges will take 5.33 kW each, and the Aux-2 bridges will take 1 kW each. The voltage at the Aux-1 bridges is 100 V, their currents will be 53.33 A. On the other hand, the Aux-2 bridges

\[
\begin{align*}
N &= \frac{V_{\text{RMS}}}{4 \cdot f \cdot A \cdot B_{\text{MAX}}} = \frac{300}{4 \cdot 20 \cdot 10^3 \cdot 9 \cdot 10^{-4} \cdot 0.2} = 21.
\end{align*}
\]

Then, the primary must have at least 21 turns. The design should consider 27 turns to satisfy the voltages scaled at a power of 3. With 27 turns in the primary, only nine turns for each Aux-1 and just three turns for each Aux-2 are required. Assuming 19 kW at 300 Vdc means 63.3 Adc at the primary winding. For this current, a 20-mm² cooper wire is enough. For the windings of Aux-1 and Aux-2, 18 and 10 mm² are required, respectively. In total, 27 turns of 20 mm² for the primary winding, 27 turns of 18 mm² for all Aux-1 windings, and nine turns of 10 mm² for all Aux-2 bridges (nine turns for each Aux-1 and 3 turns for each Aux-2) are required. Assuming a toroidal transformer with a hole five times the total area required for all the windings, the hole should have an area of \((27 \times 20 + 27 \times 18 + 9 \times 10) \times 5 = 5600 \text{ mm}^2\) (a toroid of 8-cm internal diameter is enough). Fig. 8 shows the approximate size of the high-frequency transformer for a 100-kW traction system (1 : 2 scale approximately).

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 of the diode bridges of Fig. 6 must be replaced by active rectifiers (H-bridge modules). That solution increases complexity and cost because these active rectifiers need to be controlled by means of software and additional hardware. This extra hardware is required to switch 24 new transistors with the corresponding wirings and floating supplies (or 24 optic fibers) for the 27-level inverter. This more complicated topology does not improve efficiency, because diodes are more efficient than
those reversible full transistor H-bridges. In addition, the simple diode solution does not affect the regeneration process, because Aux bridges are bypassed by switching them to 0-V operation, as shown in Fig. 9.

V. SIMULATIONS

To see the performance of the proposed system, some simulations were performed using the PSIM simulator [18]. One particular characteristic of the proposed HFL 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 proportionally change. With this characteristic, the sinusoidal waveform that feeds the traction motor remains intact, no matter how much the dc source changes. The variable dc voltage allows using the NLC strategy with the full number of levels, which gives the smallest voltage distortion (only 3% THD for all motor voltage levels). In fact, if the variable dc voltage is used, all the H-bridges (MAIN and Aux) can be kept with a fixed PWM pattern, stored in firmware mode. Fig. 10 shows the voltage waveforms using the NLC and the variable dc source, always showing the full number of levels (27 in this simulation).

Fig. 11 shows a simulation in which a constant dc supply is used. In this situation, the output machine voltage must be modified by applying PWM inside the H-bridges. For this reason and in some particular levels, the power of Aux bridges could become negative (as shown in Fig. 2), which is a situation that must be avoided. In this case, “jumping modulation” [13] is applied to jump the corresponding level, keeping it at 0 V and applying PWM between the nearest upper and lower level bridges.

VI. EXPERIMENTAL RESULTS

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

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

Fig. 14 shows that the 27 levels remain without additional distortion when the dc voltage is adjustable. The adjustment of the dc voltage can be made with a chopper, such as that shown in Fig. 5. The PWM used for the asymmetric inverter is the NLC strategy, which does not need to be modified (fixed PWM pattern). The output voltage at the traction motor is controlled with just one insulated gate bipolar transistor used in the chopper. Note that this chopper does not need the typical regenerative second transistor, because regeneration is controlled by the MAIN bridges (Aux bridges are bypassed during regeneration).

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 that moment, the
Fig. 13. Voltage waveforms at the machine terminals with the NLC (100% full voltage).

Fig. 14. Output voltage control using a variable dc supply.

Fig. 15. Transition from motor operation to regenerative operation.

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 EV being implemented will not behave like Fig. 15, because both the acceleration and brake pedals are completely independent. This oscillogram simply shows that a fast transition from a motor to a generator is achievable.

If dc voltage variation is not possible, then different PWM control strategies for the output voltage need to be applied directly on the H-bridge transistors. Fig. 16 shows a sequence of waveforms using high-frequency switching and “jumping modulation” directly applied to the H-bridges. The first oscillogram shows the waveforms with almost a full output voltage (around 150 V peak with all 27 levels). The second oscillogram shows an output voltage of around 120 V peak. This voltage represents 80% of full voltage, and for this reason, the smallest levels (Aux-2) must be jumped to avoid regenerative voltage at those H-bridges [13]. Finally, the third oscillogram 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 with only nine levels instead of 27. As can be seen, the control of ac voltage at a constant dc voltage changes the number of levels at the output, and consequently, the THD of voltage increases. The efficiency also deteriorates due to the high switching frequency.

VII. CONCLUSION

An asymmetric cascaded multilevel inverter topology based on a small and cheap HFL has been proposed, implemented, and proven. The proposed solution allows a reduction of the large number of power supplies required for these inverters to only one, allowing their application in EVs. 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 increases the efficiency of the inverter because the MAIN converters, which manage more than 80% of the total power, work at the fundamental frequency instead of 10–20 kHz, which are normal switching frequencies used 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 EVs from power ratings up to 150 kW. The HFL solution can also be used for many other purposes, such as machine drives for industry applications or high-power active front-end rectifiers. If the 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 proposed solution, multilevel inverters become a real solution for EV and HEV applications.

REFERENCES


