Design and Modeling of Multilevel Converter for Drivetrains and Stationary Applications

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L'épuisement des ressources fossiles ainsi que la tendance à la décarbonisation massive conduisent à un changement radical du paysage énergétique de demain. L'électrification croissante du secteur des transports est l'un des changements attendus dans les années à venir. Les convertisseurs de puissance joueront un rôle clé dans un large éventail d'applications. Ils devront être fiables, modulaires, efficaces et rentables. Cet article propose une étude d'un convertisseur multiniveaux qui, à première vue, répond à ces exigences.

Mots-clés: convertisseur de puissance, électromobilité, comparaison, analyse, conception, simulation, modélisation.

The depletion of fossil resources and the trend towards massive decarbonization lead to a growth of electrification around the world. As a result, electrification is intended to grow exponentially in the coming years and power electronic converters will play a key role over a wide range of applications. They are expected to be more reliable, modular, easy-to-maintain and cost efficient. This article tackles a Multilevel Converter which, at first sight, meets these requirements.

Keywords: power converter, electromobility, comparison, analysis, design, simulation, modelling.

1. Introduction

'In 2009 the European Union committed itself to reduce its greenhouse gas emissions by at least 2050 compared to the 1990 level'.[1] The depletion of fossil resources and this ambitious commitment to massive decarbonization lead the energy landscape to a major change never seen before in the coming years. Worldwide electrification of the transport sector is one of this expected change. It is slowly moving away from the main fossil energy source used today, oil[2]. Figure 1 shows that electricity is intended to take precedence over other sources of energy. Electric & Hybrid Vehicles (EV & HEV), fast charging station, micro/nano-grids, mixed power supply, energy storage, peak shaving and energy management system are all essential elements on the tomorrow's energy landscape in the transport sector. Power converters will therefore play a key role, especially in the electromobility market.

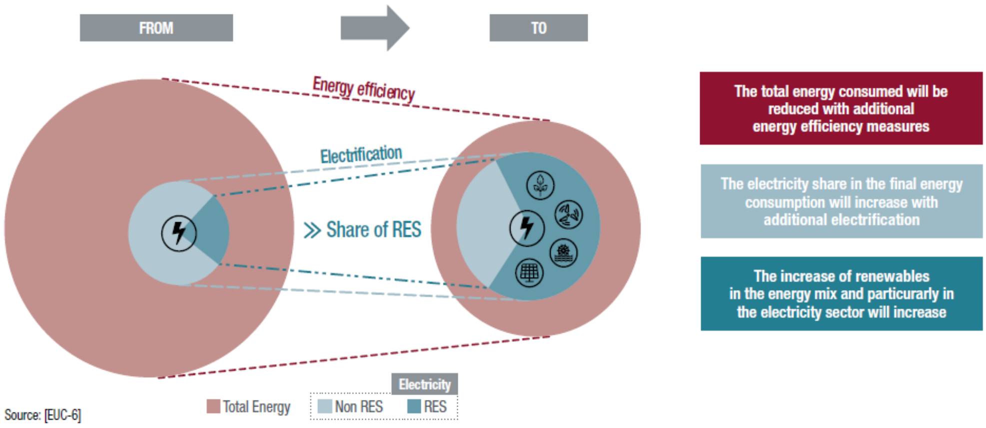


Figure 1 - 'The future energy trends' took from Elia [1]

The electromobility market can be divided into two parallel and inseparable sub-markets: Electric Vehicles (EV) and charging stations' markets. The Figure 2 illustrates the evolution of the EV market from 2013 to 2017 established by the International Energy Agency[2] (IEA). This figure shows that the electromobility market is growing up exponentially. This promising sector presents great economic and technological opportunities.

Hence, a new breed of power converter is studied to get better reliability, efficiency and modularity than classic converter: the Multilevel Converter (MLC). It will be designed, developed, analyzed and compared with another type of converter, already built and designed within the Vrije Universiteit Brussels (VUB), the Multiport Converter (MPC).

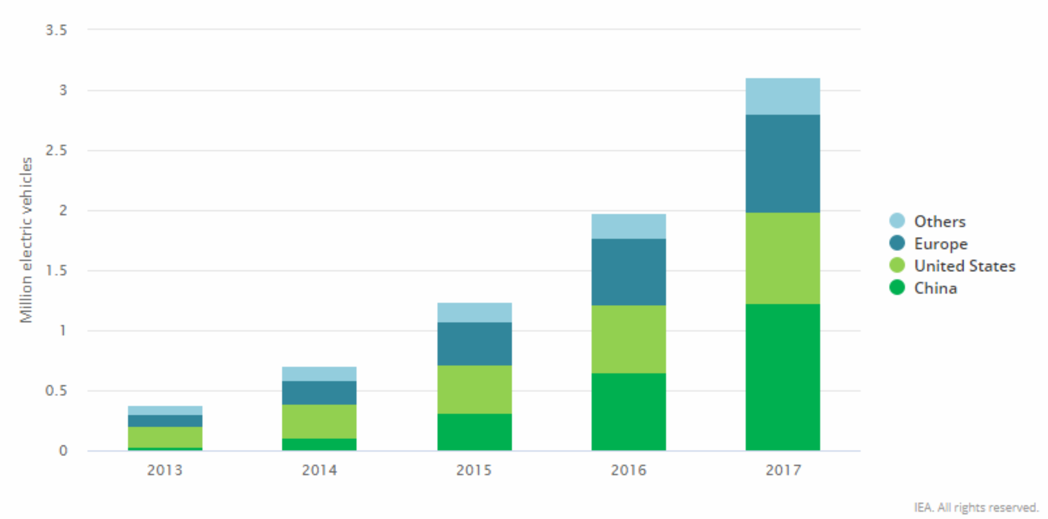


Figure 2 – Evolution of the global electric car stock (2018, International Energy Agency [2])

The basic principle of the **MLC** is to provide desired alternating voltage level at the output by using multiple isolated DC sources as an input. The DC-sources are connected in series and activated or disactivated in a defined sequence to generate desired alternating voltage level at the output. The number of levels is defined by the numbers of DC-sources.

The maximum output voltage-level can be achieved by connecting all DC sources in series, and thus, the summation of all DC sources yields the maximum voltage-level. The Figure 4 and Figure 3 show one MLC topology in particular[1] with 3 DC-sources[4] and 7 voltage levels. The complementary switches Sa_i/Sb_i are triggered to create a staircase voltage level. In addition, the full-bridge inverter is used to inverse each half-period to get AC at any required voltage and frequency.

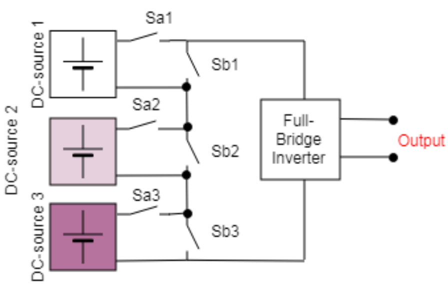


Figure 4 - Overall MLC structure, based on [4]

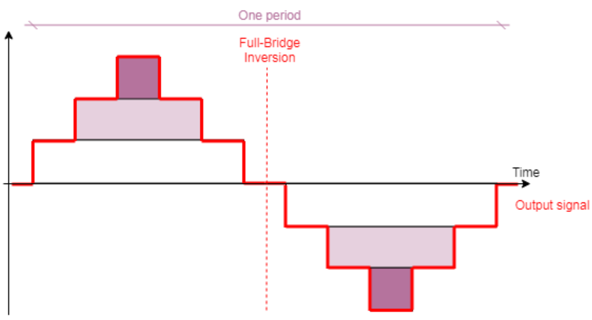


Figure 3 - 7-levels MLC output voltage signal

[1] The step topology

The advantages of MLC:

- Low harmonics and Electromagnetic Interference (EMI) in the output signal.
- Low switching frequency and switching stress.
- High modularity and reliability in case of failure of one supply.
- Versatility of the input DC-sources.
- Bidirectional energy flow.

Because of its low switching stress and its low harmonics content, the overall efficiency of the MLC is enhanced. Moreover, this converter can be used in a wide range of applications thanks to its high modularity and versatility. This converter topology deserves therefore attention in the future electromobility market.

The Multiport Converter (**MPC**) also includes several DC-sources as input but unlike the MLC those are connected in parallel. The overall architecture is illustrated in Figure 5. The basic principle of the MPC is to generate a required voltage on the DC-bus by combining energy sources of different power and voltage levels[5]. The steps generated are current steps unlike voltage steps for the MLC. Like the MLC these steps are then inverted by the full-bridge inverter. Sa_i/Sb_i are complementary switches.

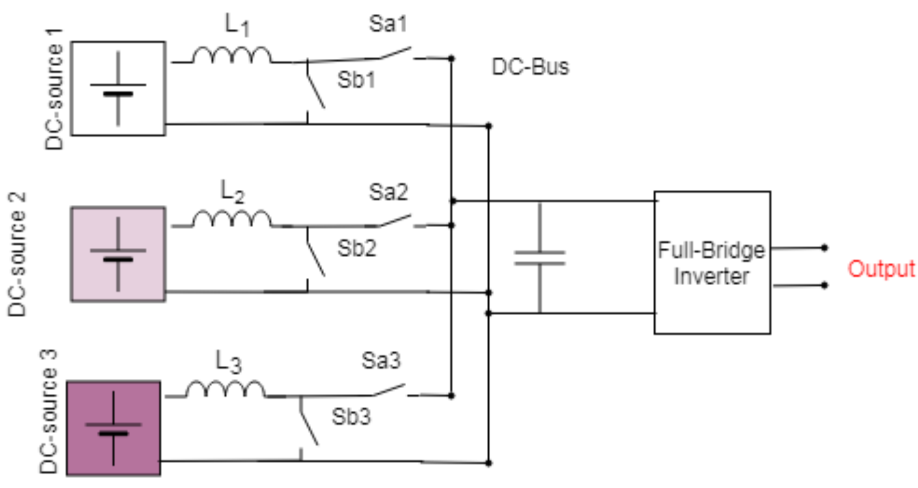


Figure 5 - Overall MPC structure, based on [5]

2. State-of-the-art of DC/AC converter topologies

Two main type of DC/AC converters can be pointed out: the single-stage and the two-stage converter. Both will be explained and then compared with the MLC & MPC.

The **single-stage inverter** is the most basic structure of converter. The Figure 6 depicts its structure. Its basic principle is inverting the DC input current into AC output current at a given frequency. The switches are turned on/off according to a specified control management (full square wave or Pulse Width Modulation).

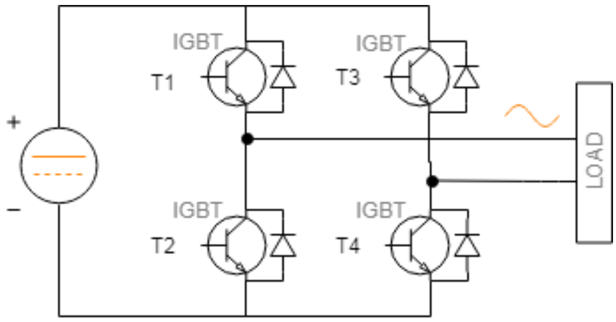


Figure 6 - One-Stage converter structure

The **two-stage inverter** has the particularity to include a DC bus between the first and the second stage of conversion. Its structure is illustrated in Figure 7. The second stage (inverter stage) handles the same role than the whole single-stage converter. The first stage however is defined as a buck/boost stage. It handles a high switching frequency for stepping-up or stepping-down the input voltage. This high frequency signal on the DC-bus reduces the size and the cost of the isolation transformer needed for galvanic isolation.

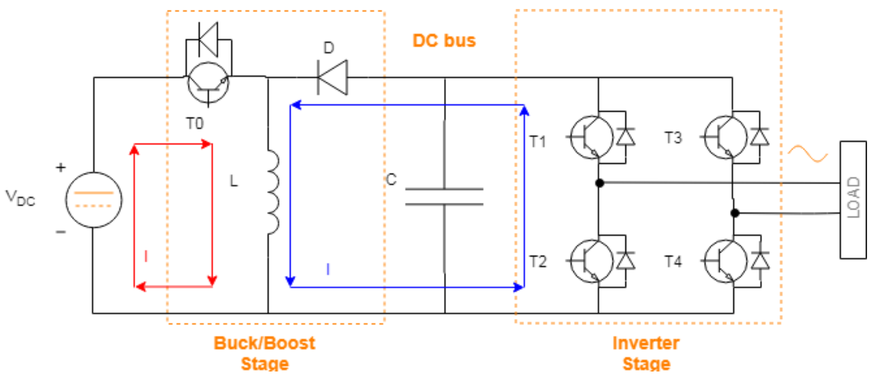


Figure 7 - Two-Stage converter structure, based on [6]

The Table 1 shows the main pros and cons of the single-stage, the two-stage and the MLC & MPC.

	SINGLE-STAGE	TWO-STAGE	MULTILEVEL	MULTIPORT
+	Simple Affordable Lightweight	Wide range of supply voltage Bidirectional DC-bus voltage regulation	High modularity & reliability Multiple DC-sources for one output, high-power application Good output signal quality Bidirectional	
-	Low modularity Low reliability Low power density High switching frequency		Higher cost Higher complexity of interface circuit	

Table 1 - Comparative study DC/AC converter topologies

As it is clear from Table 1, MLC and MPC topologies give more reliability, modularity, efficiency and power density than single/two-stage converters. Both include multiple dc-sources for supplying one output whereas single/two-stage need one bulky DC-source for the same amount of power. Plus, the several sources can be by-passed in case of defect. It allows also to get a high-power and bidirectional energy flow. Moreover, MLC & MPC generate both good output signal quality. Their switching modulation can be managed in order to get small harmonics distortion in the output signals while having reasonable switching frequency. It reduces therefore the losses and improves the overall efficiency. This statement will be proved in the rest of this article. The MLC and MPC have been not compared yet in this chapter since a section had been devoted to test and compare these two topologies. As one MPC has been already built within the VUB, the MLC deserves therefore to be deeply studied in order to build it and later compare them.

3. Selection of MLC architecture

The MLC contains numerous topologies. The main topologies are:

- Half-bridge diode clamped (HBDC) converter
- Cascaded converter
- Step converter
- Magnetic Coupled converter
- Capacitor Clamped converter

They are covered and explained in detail in several papers [3],[4],[7],[8].

In order to select the structure that best meets our specifications, these topologies are compared with respect to specific criteria.

3.1. Selection criteria

3.1.1. Total Harmonic Distortion

The THD represents the measurement of the harmonics contained in a signal in voltage and/or current. As a rule, it is expressed in percentage as the ratio of the Root Mean Squared (RMS) sum of all harmonics on the fundamental signal. In case of current harmonic frequency analysis, THD can be expressed as[9]:

$$THD = \sqrt{\sum_{h=2}^{\infty} \left(\frac{I_h}{I_1}\right)^2} \quad [\%]$$

Where I_1 is the fundamental frequency current and I_h the h^{th} harmonic current component[9]. For instance, a theoretical perfect sinewave signal contains only one harmonic, the fundamental one at the fundamental frequency. As a result, the THD value is equal to zero. As a rule, the harmonic content of a signal is computed through a Fast Fourier Transform (FFT). The FFT is an algorithm which computes the Discrete Fourier Transform (DFT). This tool allows to get a frequency spectrum listing all the harmonics contained in the signal with their amplitude.

Concerning the MLC, on the same voltage supply basis, more voltage levels there are, lower is the THD. The output signal voltage generated by an infinite number of levels would be a sinusoid. Therefore, the more levels can be added to the MLC structure, the more the THD can be reduced.

3.1.2. Redundancy switching state

The redundancy in the switching states in an architecture allows to distribute fairly the load among each DC-sources. It means that one voltage level can be generated by several switching states. If no redundancy switching states are available in the topology, the DC-sources do not supply the same energy through the load. As a result, the DC-sources voltage is unbalanced. As an example, Figure 3 and Figure 4 depict a 7 levels step structure with batteries as DC-sources. The first level of voltage can be generated either by the first, the second or the third battery as they have the same voltage level. There is therefore a switching state redundancy. In order to avoid the early discharge of one of the batteries, the first voltage level should be hence generated alternatively by the first, the second and then the third battery. All batteries supply then the same energy to the load. The same is true for the second and the third level of voltage.

3.1.3. Modularity

The modularity criteria consider two aspects. First, the size of the structure. If the overall architecture is compact or not. Secondly, the ease of connecting or disconnecting a DC-sources into the MLC structure. It means that adding a cell into the MLC architecture does not change the overall structure or complicate the architecture.

3.1.4. Reliability

A reliable and robust MLC consists on a structure that can avoid any supply lack. Practically, it means, on the first hand, that the structure does not depend on only one DC-source for supplying the load. On the other hand, it means that the architecture includes a bypass procedure in the event of a cell failure. A spare cell is then connected to replace the failed cell. It is therefore linked to the modularity criteria. The more cells can be added to the structure, the more spared cells are available and the more reliable the structure is.

3.1.5. Complexity

This feature is directly related to the number of switches. For the same level of voltage, MLC topologies include different number of switches. On the first hand, the switches complicate the interface circuit. Each switch is controlled by a gate driver. The more switches there are, the more gate drivers and the more complicated the structure is. On the other hand, it complicates the switching control strategy.

3.1.6. Switching frequency

The voltage stress, expressed as $\frac{dv}{dt}$, is related to the switching frequency of the converter. As the switching frequency increases, the voltage stresses on switches increase. A high switching frequency generated therefore losses and Electromagnetic Interference (EMI). It leads to low efficiency and disturbance on the output signal quality. This criterion is not influenced by the MLC topology but by the switching strategy used. The particularity of MLC is to present a very low switching frequency provided that an appropriate modulation technique is applied. For instance, MLC structure can be used with a PWM modulation technique. The switching frequency is therefore higher, and the losses increase.

3.2. Comparison

In order to compare these topologies on the same basis, the same number of levels must be set for each structure. On the same supply voltage basis, the number of levels influences the quality of the signal. The number of levels should also consider the practical feasibility. It is therefore convenient to set a number of voltage levels which ensure a low THD value and which is feasible to build in practice. According to scientific papers[3],[10], 13 voltage levels seems to be a good quality/feasibility trade-off. Theoretically, all the structures generate the same signals (thus the same THD) if the same switching strategy is applied.

The 13-levels MLC topologies are compared through Figure 8.

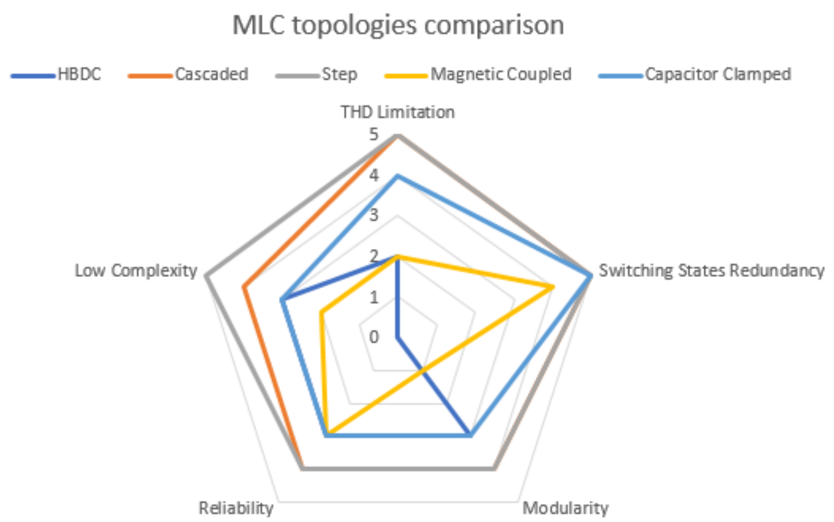


Figure 8 - MLC topologies comparison chart

As it is clear from the comparison, the best topologies for our applications are step and cascaded topology. They offer indeed the best choice in terms of:

- Complexity: the structures are simple and repeatable.
- Reliability: separated dc-sources can be by-passed in case of failure and do not included any ‘risky’ component (such as transformers). The failed cell can be replaced without affecting the rest of the structure.
- Modularity: separated dc-sources are used for generating the signal and high number of levels can be achieved.
- Efficiency: since soft-switching frequency can be used to decrease power loss in the converter and levels can be easily added which decrease the THD.

Finally, the difference between cascaded and step topologies lies on the cost. Since cascaded structure needs more switches and diodes, its capital cost is higher than the step structure. Moreover, less gate drivers means easier control strategy and less complicated interface circuit.
As a result, the step topology is taken as the best multilevel topology for our application.

3.3. Final architecture

The final MLC architecture is now set up as pictured Figure 9.

- Each DC-source is connected to a half-bridge. The two switches Sa_i/Sb_i within each half-bridge are complementary to avoid short-circuiting the cell. Figure 10 depicts the output voltage signal V_{out}. The firing angles α_i/β_i define respectively when the related switch Sa_i is turned on/off. They shall be defined wisely through the modulation technique.

- The full-bridge inverts the current in the load to generate an alternating voltage at the required frequency. The switches S1/S2 and S3/S4 are complementary. The current is positive by switching on S1/S4 and negative by switching on S2/S3. The switching frequency is hence 50 Hz. It must be synchronized with the half-bridges.
- Each DC-source generates one level of voltage V_{DC}. The whole converter shall supply 230 V_{RMS}. There are 6 DC-sources. As they have the same level of voltage, V_{DC} should be equalled to:

$$\frac{\sqrt{2}\,230}{6} = 54.2 \quad [V]$$

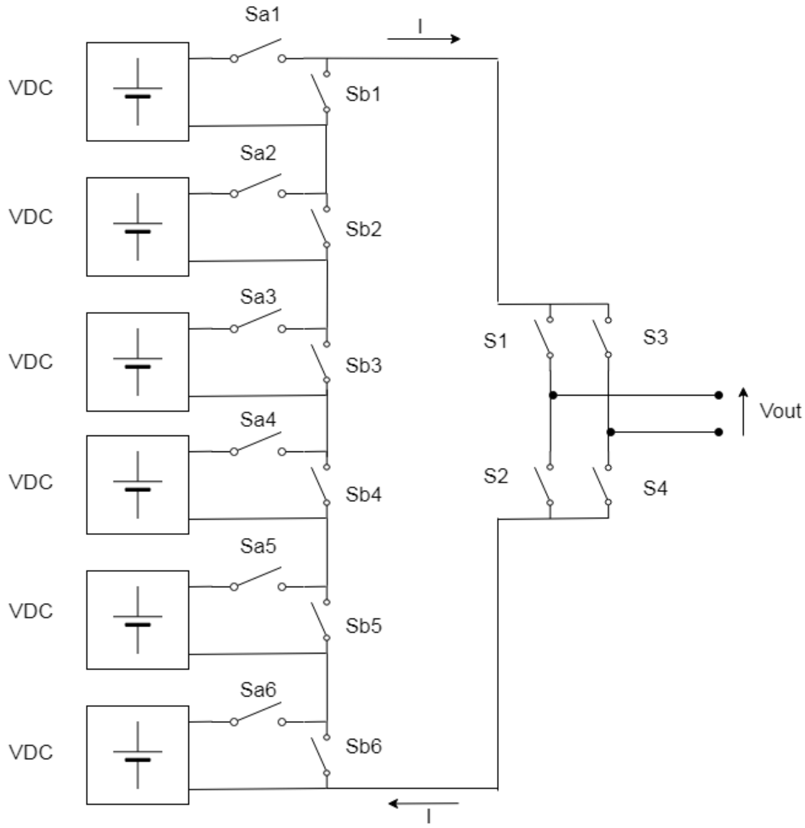


Figure 9 – Overall 13-levels step structure

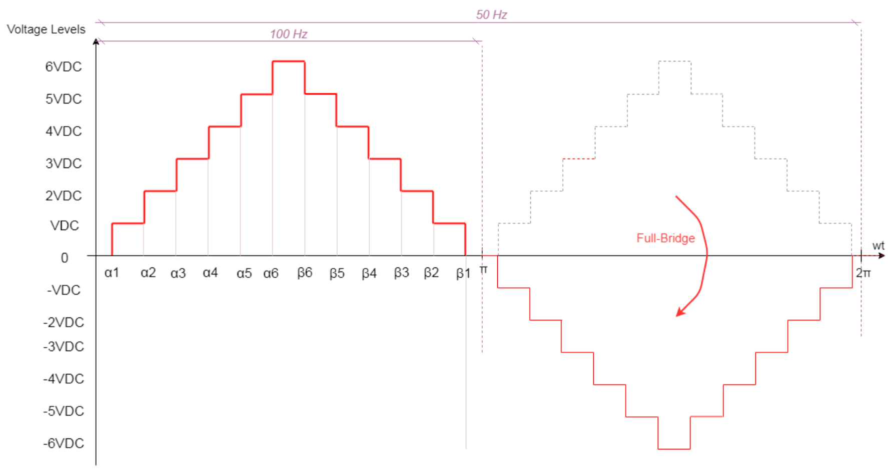


Figure 10 – Output voltage signal for 13-levels step topology

4. Modeling, Simulation and Hardware implementation of Multilevel Converter

4.1. Hardware

The hardware components needed to build the MLC are:

- 6 DC-sources of approximatevely 54.2 V each.

- 16 switches SiC-Based Metal Oxide Semiconductor Field Effect Transistor (MOSFET). These MOSFET must withstand the maximum voltage and current that flow into the circuit. They shall also be placed on heatsink to allow heat dissipation during operation. To enhance heat dissipation, two cooling fans are included in the structure.

- 16 Isolated Gate Drivers. In order to avoid any short-circuits between MOSFETs and to simplify the voltage control of those, the gate drivers must be supplied separetaly by isolated DC/DC supply.

- 1 controller or Digital Signal Processor (DSP). The kit board uses is C2000 model with embedded TMS320F28335 DSP from Texas Instruments®.

- 1 main supply for electronic components. One AC/DC converter is used to supply the controller as well as the isolated DC/DC supplies for the gate drivers. The power of the main supply must cover the sum of all components consumption.

4.2. Control Algorithm Simulations

Three main switching strategies are implemented on the MATLAB/Simulink® model of the MLC structure and then compared in terms of THD. The model simulates the MLC structure through an inductive load.

4.2.1. Basic technique

This technique consists on dividing each voltage steps into equal time basis over one half-period. The full bridge inverts each half-period to get an output signal frequency of 50Hz. The switching frequency of the half-bridge switches is therefore 100 Hz. The period of each half-bridge pulse is 0.01 second. In order to get equal time steps, the half-period shall be divided by the number of levels. The Figure 10 depicts this basic technique.

The Figure 11 depicts the voltage and current measurements at the load for the simulation of the basic technique modulation. The current is smoothed out thanks to the inductance in the load. The Figure 13 and Figure 12 illustrate respectively the FFT analysis for the output voltage and current signals. The THD values respectively equal to 15% and 11%. It can be observed that both frequency spectrums contain odd harmonics. On the first hand, the 3rd voltage harmonic has a magnitude of about 11% of the fundamental i.e. 32 V. On the other hand, the 3rd current harmonic has a magnitude of about 10% of the fundamental i.e. 0,96 A. Because of a high 3rd current harmonic a smoothing inductance shall be added so as to enhance the output signal quality. This smoothing inductance makes the converter bulkier and more expensive than a converter with lower THD. It is why cancelling the odd harmonics is wised.

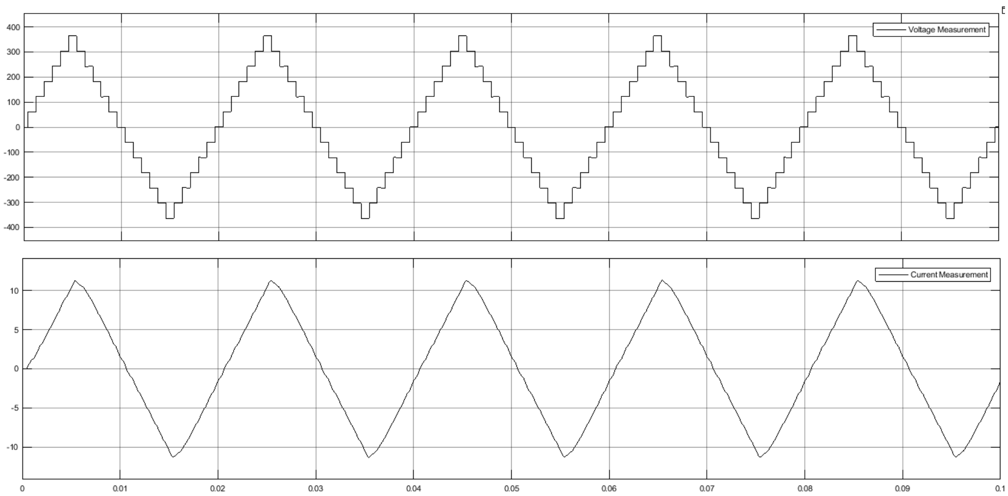


Figure 11 - 13-levels MLC voltage and current signals simulation with basic technique modulation

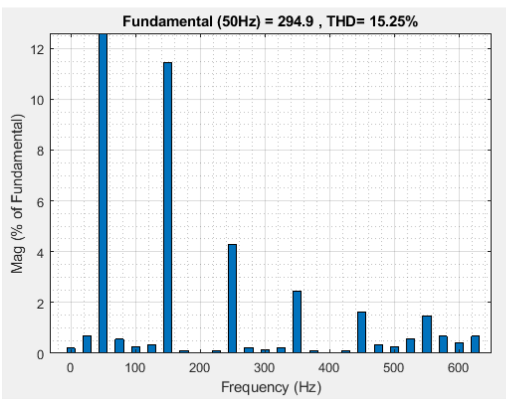


Figure 13 - Voltage harmonics spectrum for basic technique modulation

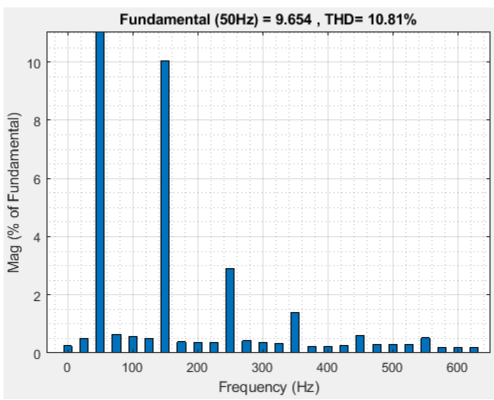


Figure 12 - Current harmonics spectrum for basic technique modulation

4.2.2. Pulse Width Modulation

The basic principle is to compare a carrier signal (mainly a triangle signal) at high frequency with a reference signal. The reference signal is a sinusoid that have the same frequency needed at the output. When the reference sinusoid is higher than the carrier, a logic gate sends a pulse. As a result, the successive pulses created have different widths. The mean value of each pulse is proportional to its width. In terms of mean value, the output signal generates therefore a sinusoid. The Figure 16 depicts the voltage and current measurements at the load for the simulation of the PWM technique. As expected, the switching frequency is higher than other modulation methods. As a result, the switching losses increase and hence decrease the overall efficiency of the converter. However, the output current signal is close to a perfect sinusoid. The Figure 14 and Figure 15 illustrate the frequency spectrum for the voltage and the current output signal. The current THD equals to 2,65%. It is indeed much lower than the previous modulation technique. The quick commutation for each step as well as the inductance in the load increases the current signal quality.

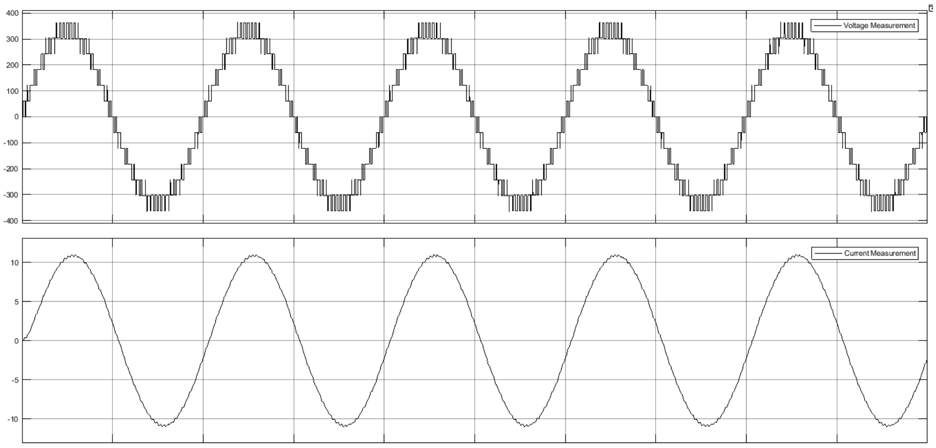


Figure 16 - 13-levels MLC voltage and current signals simulation with PWM

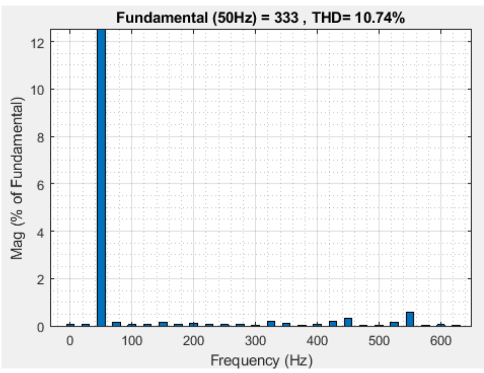


Figure 14 - Voltage harmonics spectrum for PWM technique

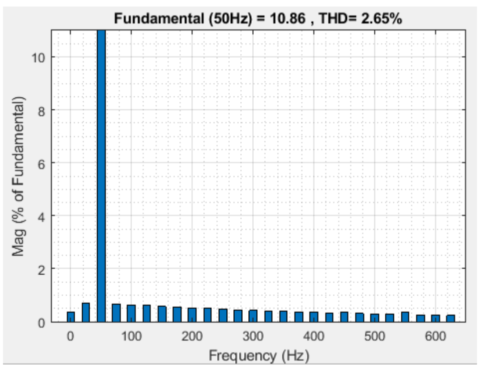


Figure 15 - Current harmonics spectrum for PWM technique

4.2.3. Selective Harmonic Elimination

The Selective Harmonic Elimination (SHE)[10] technique aims to eliminate the odd harmonics of the output signal. It can be achieved by optimizing the complementary firing angles α_i and β_i. The optimization aims to find out the best switching times for approaching as close as possible to a sinusoid. The Figure 17 depicts the voltage and current measurements at the load for the simulation of the SHE technique. The voltage signal is close to the signal of the basic modulation technique. The steps have however different duty cycles. The voltage as well as the current are therefore closer to a sinusoid than the first technique. The Figure 19 and Figure 18 illustrate the harmonic spectrum for the voltage and the current signal. Both THD values are much lower than the basic technique. The THD voltage equals to 8% and the THD current equals to 3%. These values are in the same range than for the PWM technique. The switching frequency is however lower than the PWM technique. There is thus lower stress on the components and lower switching losses. The efficiency is higher while having relatively the same quality of output signal. Furthermore, this technique is easier to implement in a controller than a PWM method with several carriers.

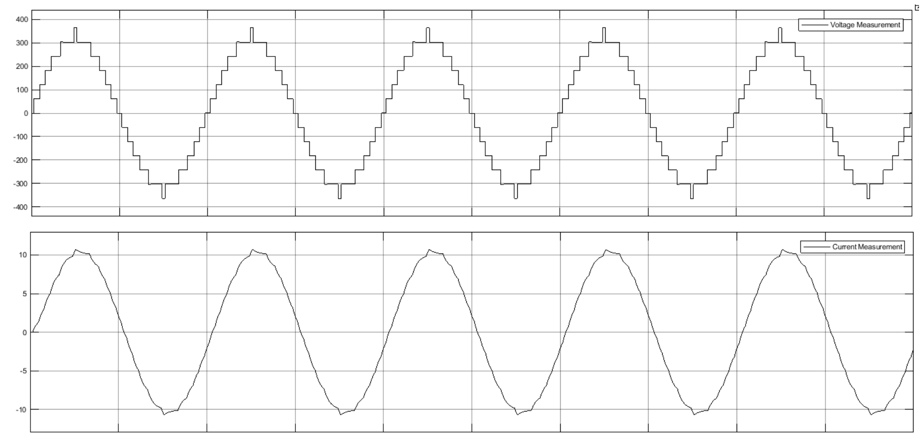


Figure 17 - 13-levels MLC voltage and current signals simulation with SHE

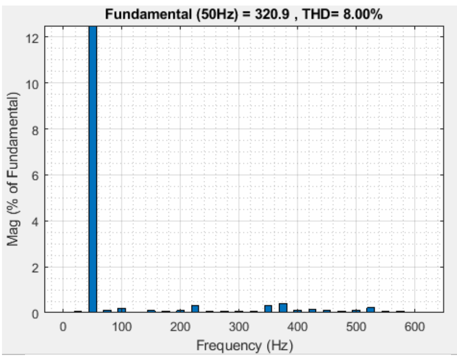


Figure 19 - Voltage harmonics spectrum for SHE

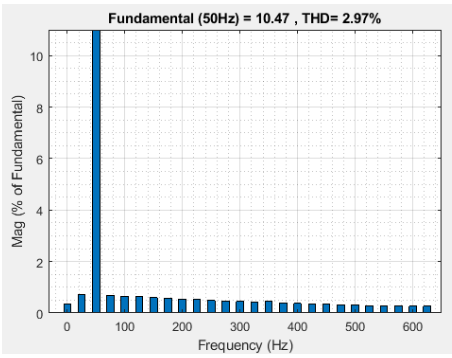


Figure 18 - Current harmonics spectrum for SHE

4.3. Modulation Techniques Comparison

Conclusions can be pointed out:

- The basic modulation technique generates the highest THD. It is however the easiest technique to implement in a controller if more levels are added. As the number of levels increase, the equation for computing the firing angles does not change.
- The PWM technique generates good output signal quality. The THD value for the current is the lowest. The major drawback is the high switching frequency required. The switches are thus more solicited and the losses are higher. The PWM technique has a bad impact on the overall efficiency. Moreover, this technique is more complicated to implement in a controller.
- The SHE technique generates good output signal quality while having low switching frequency. It is the best trade-off between switching frequency and THD. The efficiency is therefore the highest. The major drawback is the complexity of computing the firing angles. It required the use of a powerful algorithm to compute the right firing angles. Moreover, as the number of levels change, the firing angles shall be recomputed. This technique depends on the number of levels as well as the DC-source voltage.

The SHE technique is chosen as the best suitable modulation strategy for our application. More information about the algorithm can be found in scientific paper[11]. This technique is therefore implemented in the MLC structure.

5. Validation and Experimental results

5.1. Simulation comparison between Multilevel and Multiport

This part focus on the comparison in terms of THD between the MLC simulation model with SHE technique (see 4.2.3. Selective Harmonic Elimination, p.15) and the MPC simulation model.

The MPC simulation model uses the 3rd Harmonic Injection Modulation (HIM) with PWM as modulation technique.

The Figure 20 and Figure 21 depict respectively the voltage and current output signals for the MPC as well as their specific harmonic spectrum.

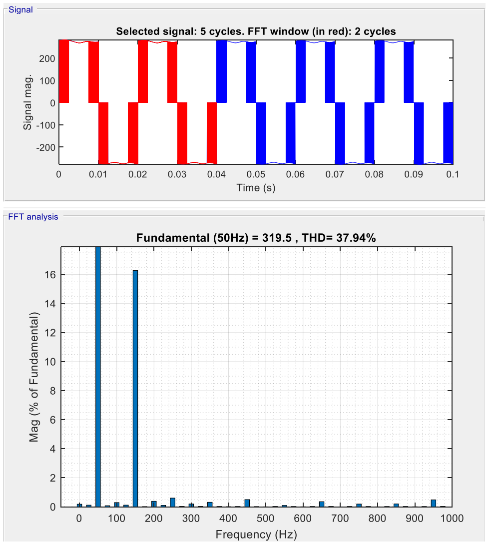


Figure 20 - 6-ports MPC output voltage signal simulation and harmonic spectrum

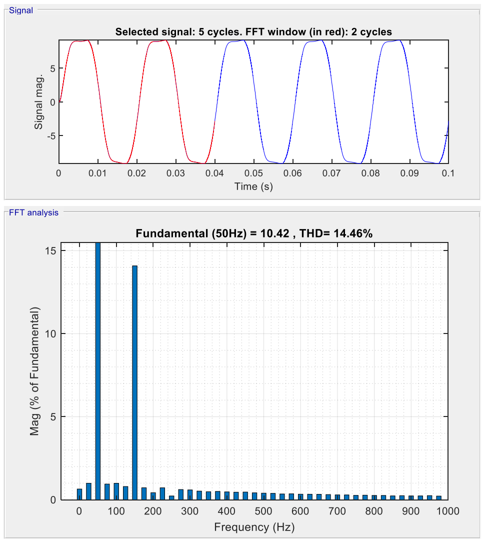


Figure 21 - 6-ports MPC output current signal simulation and harmonic spectrum

The THD value for the voltage is about 38%. This value is much higher than all others MLC modulation techniques already described. Consequently, the THD value for the current is also higher (about 14%). Moreover, the MPC structure includes a boost stage for each level (see Figure 5, p.4). The switching frequency needed on each boost stage is much higher in order to step up the voltage on the DC-bus. The switching frequency equals to 100 kHz. The components are more solicited and hence the switching losses are higher. The output voltage can however be easily regulated by changing the duty cycle of the boost switches. Different DC voltages can therefore be used and then adjusted to get the required voltage on the DC-bus.

In conclusion, for the same load, the MPC generates signals which contains more harmonics than the MLC. The modulation technique used for the MPC requires much higher switching frequency than the SHE technique used for the MLC. Moreover, the MLC does not need of inductance in its structure. It has less components and hence lower cost than the MPC. However, both have low complexity of interface circuit.

5.2. Multilevel low voltage tests

This part addresses the comparison between the theory and the practice. The MLC built is tested and then compared with simulation. Due to unavailability of 61 V DC-sources, the tests on the MLC have been performed in low voltage. The behaviour is however the same in low voltage applications. Six DC-sources of 12V each are therefore used instead of 61V. The load used is a resistive type of 20Ω. In order to compare theory and practice on the same basis, simulations with the above-mentioned conditions must be conducted. First with the basic modulation technique and then with SHE technique.

5.2.1. Basic modulation technique

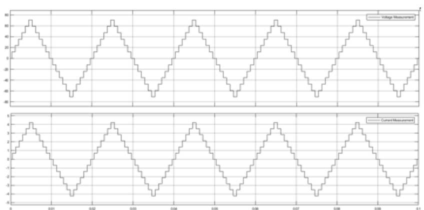
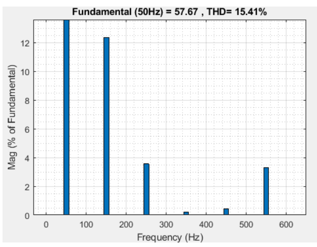
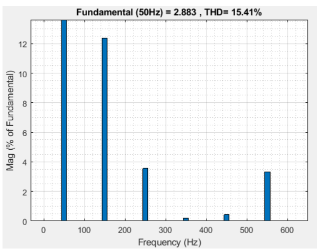
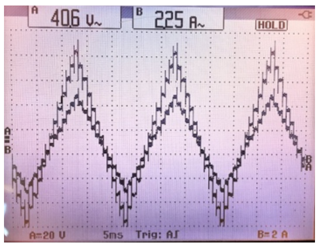
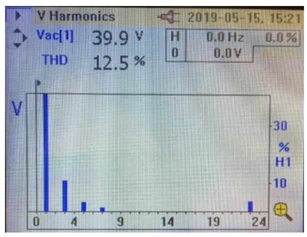
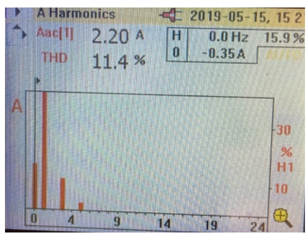
	SIMULATION				**EXPERIMENTAL RESULTS**			
	V_{AC} [V]	I_{AC} [A]	P [W]	THD [%]	V_{AC} [V]	I_{AC} [A]	P [W]	THD [%]
OUTPUT	41	2,1	86	15	40	2,3	90	*(Voltage)* 12 *(Current)* 11
DATA	  				  			

Table 2 – Basic technique comparison between simulation and test results

The data in Table 2 are in the same range of value. This test proves that the demonstrator works. The voltage as well as the current signals behave as expected in the simulation. The voltage and current THD are even lower than the simulation results. The load includes indeed a parasite inductance. This inductance is due to the underground cables which connect the resistive load in series throughout the VUB lab. As a result, the current is smoothed out and the THD is lower than the simulation.

5.2.2. SHE modulation technique

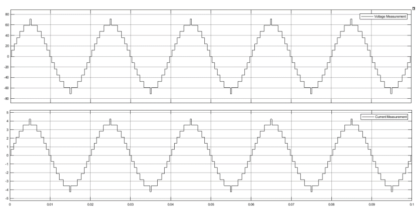
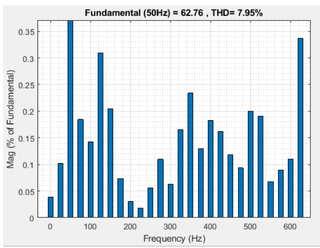
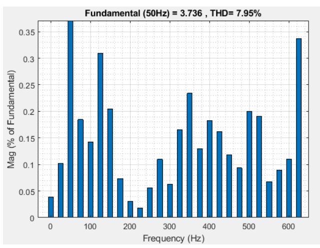
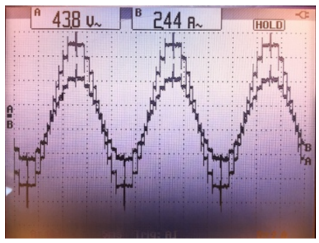
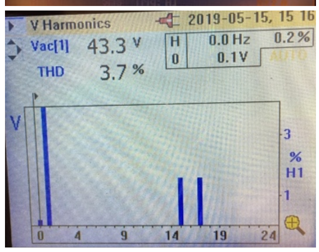
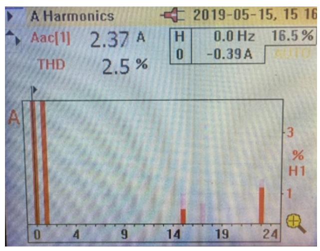
<table>
<tr><th></th><th colspan="4">SIMULATION</th><th colspan="4">EXPERIMENTAL RESULTS</th></tr>
<tr><td rowspan="2">OUTPUT</td><td>V_{AC} [V]</td><td>I_{AC} [A]</td><td>P [W]</td><td>THD [%]</td><td>V_{AC} [V]</td><td>I_{AC} [A]</td><td>P [W]</td><td>THD [%]</td></tr>
<tr><td>44,6</td><td>2,2</td><td>100</td><td>8</td><td>43,8</td><td>2,4</td><td>104</td><td>(Voltage) 4
(Current) 2</td></tr>
<tr><td>DATA</td><td colspan="4">

</td><td colspan="4">

</td></tr>
</table>

Table 3 – SHE modulation technique comparison between simulation and test results

The values in Table 3 are also in the same range. As previously discussed, as the load includes a parasite inductance, the THD is lower than the simulation. Moreover, the frequency spectrum in the experimental results shows that the odd harmonics (to the 11^{th}) are completely cancelled out compared to the previous test with basic modulation. This proves the major advantage of the SHE modulation technique. The output signals contain very low harmonics.

6. Conclusion and future work

This article studied the design process of a 13-levels step MLC demonstrator. Advantages of generic MLC have been stated compared to main DC/AC converters. The MLC is modular, versatile, bidirectional and efficient. It generates low EMI and a good output signal quality. Main topologies of MLC have been compared based on specific criteria. The step topology resulted on the best topology for our applications. It is more modular, reliable and cost efficient than others. This topology has been designed in terms of hardware and algorithm. Different modulation techniques have been addressed and implemented in simulation models. The SHE technique resulted on the best strategy in terms of THD and switching frequency. The MLC and the MPC already built within the VUB have been compared through simulations. The MLC generates lower THD in the output signal and requires lower switching frequency than MPC. The MPC is more modular. The MLC demonstrator has been built and tested. The tests results comply with the simulations results.

Some suggestions for improvement as well as key trends for future work can be pointed out:

DC-sources with different voltage levels. The SHE modulation technique considered within this article cannot be applied with different voltage levels. It must be adjusted. A voltage regulation stage (such as Buck/Boost) can be added for each source. It will regulate the voltage and allow to have different levels of voltage for the DC-sources. Further testing can be conducted with several DC-sources such as photovoltaic cells and batteries.

Bidirectional applications. The converter has been designed as an inverter. It can be however used as a rectifier provided some improvements. This versatility is one of the most important feature of power converters for the tomorrow energy landscape. EV growing consists indeed on a huge opportunity for grid energy storage. The energy supply and demand could be hence more balanced. Future smart charging stations will decide to charge the vehicle or discharge it according to the grid balance. It is called Grid to Vehicle (G2V) and Vehicle to Grid (V2G) system[36]. The MLC is in line with this future trend. It can be implemented between the grid and the EV batteries as on-board charger. On the first hand, the grid can charge the batteries when energy storage is needed. On the other hand, the batteries can supply the grid when a pick demand appears. In both cases, the MLC can handle the bidirectional conversion. The modulation strategy must be updated and further work on the subject must be conducted. This is one application example among many others. The MLC can be used wherever bidirectional conversion is required with several DC-sources available.

In conclusion, the MLC designed, built and analyzed within this article deserves to be further studied in the future. Its versatility, modularity, reliability and efficiency are such key features essential for the tomorrow energy landscape. The paths of improvement are numerous and promising technologies will reinforce its advantages. The demonstrator proposed has therefore proved what the MLC can be capable of. It marks the beginning of an interesting technological journey which could solve the tomorrow's energy challenges.

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