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Comparative Study of Different Multilevel DC/DC Converter Topologies for Second-Life Battery Applications

Mohamed Abdel Monem[1,2], Omar Hegazy[1], Noshin Omar[1]
Bart Mantels[2], Grietus Mulder[2], Peter Van den Bossche[1] and Joeri Van Mierlo[1]
[1]*Vrije Universiteit Brussel, Pleinlaan 2, Brussels, 1050, Belgium, mohamed.abdel.monem@vub.ac.be*
[2]*VITO, Unit of Energy Technology, Boeretang 200, Mol 2400, Belgium, mohamed.ismail@vito.be*

Abstract

This paper is part of a research project, which aims to investigate the possibilities of using the second life batteries after their replacement from plug-in electric vehicles (PHEVs), hybrid electric vehicles (HEVs) and battery electric vehicles (EVs) for smart grid applications. Batteries which are used for vehicular service cannot be used once that the capacity becomes less than 70% - 80% [1]. The remaining capacity of the battery can be utilized for stationary applications during peak load hours and to reduce the environmental pollution. These batteries are defined as second life batteries. In these applications, the power electronic converters (PECs) play an important role in the development of high performance integrated systems. It means that the performance of the second life batteries mainly depends on the characteristics of the PECs, which are utilized to achieve the integration of the second life batteries with the smart grid. Therefore, this paper represents a comparative evaluation of different multilevel DC/DC converter topologies that can be used to connect the second life batteries to smart grid. Furthermore, the advantages and drawbacks of the most popular multilevel DC/DC converter (MLDC) topologies are presented in detail. In this paper, a selected harmonic elimination (SHE) technique has been used to realize the control system of the multilevel DC/DC converter, and its influence on the performance of each battery module is analyzed. These topologies are designed and verified by using MATLAB/Simulink environment.

Keywords: Second-Life Batteries, Multilevel DC/DC Converters, Selected Harmonic Elimination, Total Harmonic Distortion

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1 Introduction

In few years, a large number of used batteries will be introduced to the market. As a result, it is necessary to find the appropriate power electronic converter that can be used to connect the second life batteries to smart grid applications. Battery packs can be removed from the PHEV, HEV and EV after their useful life in the vehicle power trains. These battery packs can be combined with other battery packs or modules that are obtained from other applications in order to create large-sized systems [1,2]. Stationary battery applications often do not have the severe weight and volume constraints of the PHEV, HEV and EV applications. Therefore, this can lead to lower energy and power requirements (on a unit weight or volume basis) for batteries. Since the reuse of the PHEV, HEV and EV batteries are still expected to be able to store and deliver a substantial energy, it is possible that they might satisfy the requirements of these applications [3-7]. The reuse of second life batteries can provide an opportunity to reclaim a portion of the purchase price of the battery and thus effectively reducing its initial cost. This would also make a lower cost for the progressive batteries that are available in the stationary energy storage market. Besides, it can accelerate the establishment of a sustainable market for advanced PHEV, HEV and EV battery technologies. There are two scenarios to use the second life batteries for the stationary applications: 1) classify the batteries into groups and select the suitable application for each group based on the characteristics within each group of batteries, and 2) reconfigure all types of batteries in the same application by using different power electronic topologies. The complete system of any stationary application consists of a battery system, power electronic topologies, and AC filters. It should be pointed out that the power electronic converters and the control strategy can be used to improve the lifespan of the second life battery system, fault-tolerance of the used battery modules, complexity, total harmonic distortion (THD) of AC side and the overall cost. However, the reliability of the second life batteries is an important issue as individual batteries may suffer from degraded performance or failure. Therefore, the design of the converter topology could influence the overall system performance.

As a consequence, this paper represents a literature overview of multilevel DC/DC converter topologies that may utilize fewer numbers of switches, high reliability and high efficiency. By using a multilevel DC/DC converter (MLDC), the electric power demand can be shared between the battery modules based on the performance of each battery module (such as capacity and state of charge (SoC)) in order to increase the lifetime of the second life batteries. Then, three popular topologies of multilevel DC/DC converters are studied to demonstrate the advantages and drawbacks of each topology and to realize its feasibility for the second life battery applications. A multilevel DC/DC converter can synthesize a desired output voltage from several DC voltages (such as battery modules) as inputs [8]. The research and development for these types of converters is gaining popularity, especially for high-power and high-voltage applications due to their reduction in losses and THD [10]. Furthermore, the size of the passive filters can be reduced leading to a compact size for the overall system.

In addition, MLDC can produce output waveforms with a better harmonic spectrum and can provide a high-power quality, high reliability and a good electromagnetic compatibility (EMC). The cascaded H-bridge and the diode clamped topology are the most popularly hardware implemented topologies at present, especially in the growing technological field of renewable energy. These inverters have some disadvantages. One of the most obvious disadvantages is that numerous power semiconductor switches are required leading to a complex system control. As a result, a multilevel DC/DC converter can be used to overcome the previous problems [8].

2 Multilevel Converter

Power electronic converters are a main part of modern electric circuits, which are used to convert the electric energy from one level of voltage, current or frequency to another by using electronic switching components. Regarding different electric applications, various power converters with optimum modulation technique should be used to deliver the desired electric energy to the load with maximum efficiency and minimum cost [8].

2.1 Overview

One of the most significant recent advances in power electronic converters is the multilevel inverter. Besides, there are several multilevel converter topologies have been developed [10-14]. Fig. 1 shows the most common multilevel power converters and the classical two-level converters. The elementary concept of a multilevel converter is to use a series of power semiconductor switches with several lower voltages dc sources to perform the power conversion by accumulating a staircase voltage waveform. Capacitors, batteries, and renewable energy voltage sources can be used as the multiple dc voltage sources. Multilevel converter gives significant advantages compared to the conventional converters, which are known as two-level converters. These advantages are high-power quality waveforms, low switching losses, high-voltage capability, low electromagnetic compatibility (EMC) [12–14].

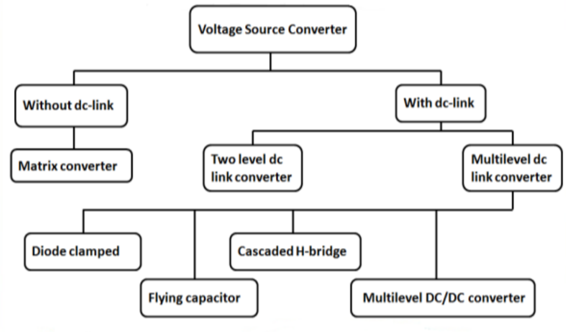


Figure 1: Most common voltage source converters.

2.2 Multi-level converters for used battery

The Cascaded H-Bridge Converter (CHBC) and the Multi-Level DC/DC Converter (MLDC) consists of a series connection of separate single modules. Each dc module requires an isolated dc input. These topologies are suitable for applications where separate dc voltage sources are available, such as photovoltaic (PV) systems, fuel cells and batteries [22-24]. Thus, CHBC and MLDC can be used to feed the electric load from separate battery modules. Multi-level DC/DC converter has significant advantages compared to cascaded multilevel inverter such as: 1) low number of switches and diodes as shown in Table 1, 2) low power loss and high efficiency, 3) high reliability and less complicated. As a result, the MLDC can be used as an optimum solution to reuse the batteries which are removed from vehicular service. Used batteries are removed from vehicular services not only when their capacity reach to 80% of the rated capacity but also when their internal resistance becomes twice than their initial value [2]. It means that these batteries should be characterized by testing all of them. As a consequence, the used batteries will be divided into modules, where each module contains some of the cells (for example: 8-16 cells), which are connected in series. As mentioned, there are two scenarios to reuse the used batteries for the stationary applications. In the latter scenario, it is important to know that the performance of each module is differed from one module to another. Therefore, each module should feed a portion of the load demand based on the characteristics of each module. Each battery module can share a portion of the total electric energy that is required to feed the load. The location of each module in the multilevel DC/DC converter based on the performance of each battery module (such as capacity, internal resistance and life cycle) in order to increase the lifetime of the second life batteries. Fig. 2 demonstrates a 13-level single phase multilevel DC/DC converter. Furthermore, Fig. 3 demonstrates the current drawn from each module, based on the location of each module in the electric circuit. As shown from Fig.3, each module contributes by supplying a portion of the electric energy for feeding the electric load.

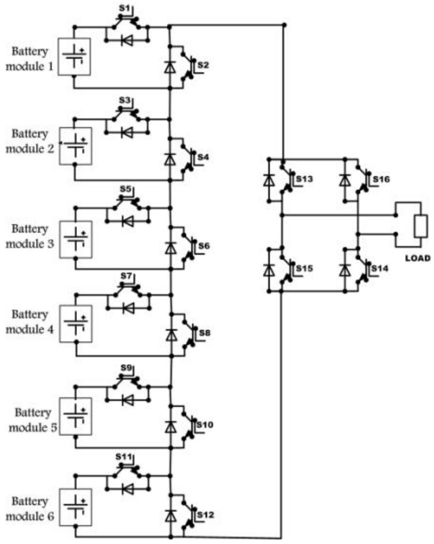


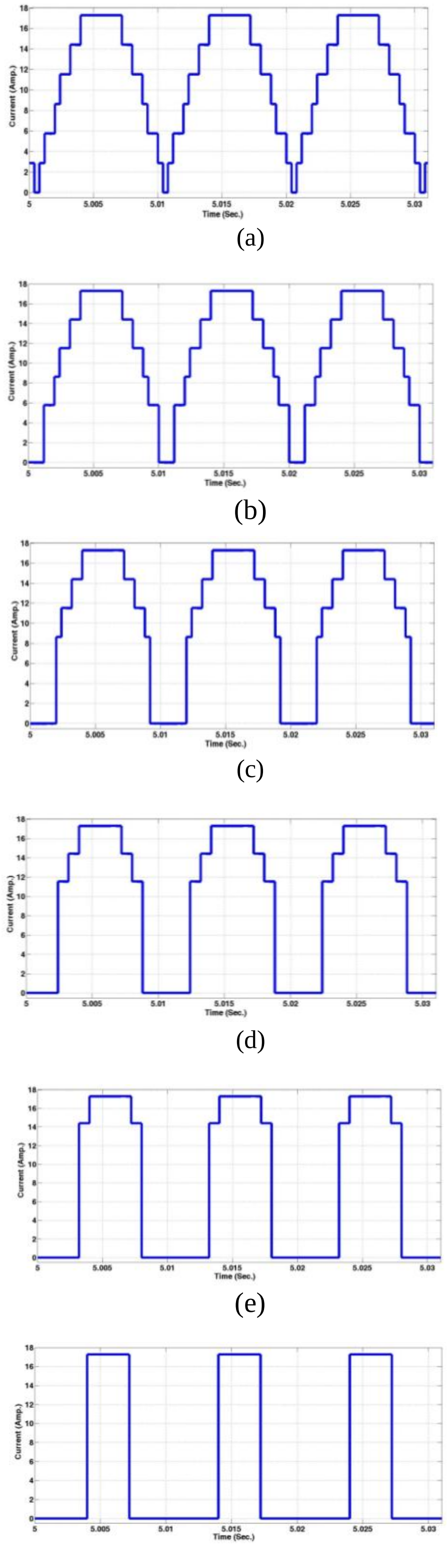
Figure2: 13-level single phase multilevel DC/DC converter.

Table1: Number of switches and diodes of 7-level single-phase multi-level converters

	(CCMI)	(MLDC)
Number of switches	24	16
Number of diodes	24	16

3 MLDC comparative evaluation

This paper represents a comparative study of the most popular multilevel DC/DC converter topologies. Fig. 4 shows three topologies of popular multilevel DC/DC converters [19,20,21]. This research will focus on three significant parts to compare between three popular multilevel DC/DC converters as follows: 1) complexity and efficiency, 2) fault-tolerance and the percentage of continuity, 3) the possibility of loading.



(a)

(b)

(c)

(d)

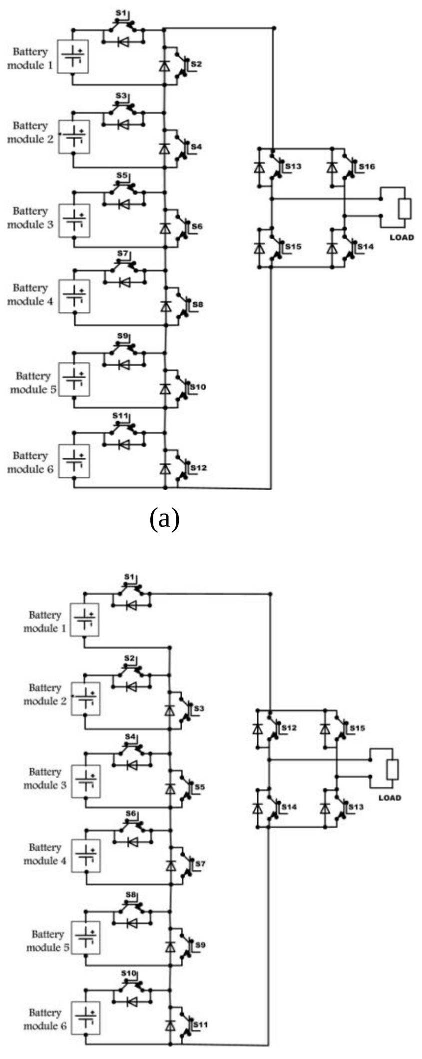
(e)

(f)

Figure3: The current of one cell from each module.
(a) Module 1, (b) Module 2, (c) Module 3,
(d) Module 4, (e) Module 5, (f) Module 6.

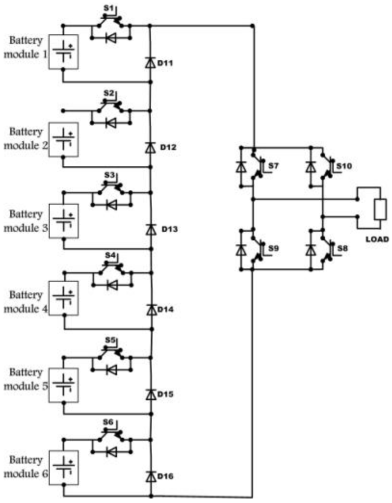
3.1 The operation of MLDC

All topologies have a set of series DC/DC converter blocks as shown in Fig. 4. For an example, from the topology 1, switch S1 and switch S2 should be conducted at different instances in order to prevent any short circuit across the voltage source. When the S1 (S2 off) is turned on the output will be equal to V_{dc} and when S2 is turned on (S1 off) output voltage will be zero. Where V_{dc} is the output voltage of each battery module.



(a)

(b)



(c)

Figure4: Multi-level DC/DC converter. (a) Topology 1[19], (b) Topology 2[20], (c)Topology 3[21].

Therefore, the magnitude of the DC link is the sum of the voltages produced by each module.

In the Fig. 5, α1, α2, α3, α4, α5 and α6 are the switching angles for six battery modules, and β1, β2, β3, β4, β5 and β6 are corresponding supplementary angles for α1 to α6 respectively. The magnitude and THD content of output voltage mainly depend on those switching angles. Therefore, these angles should be selected properly. For a 13-level MLDC, there are six battery modules per phase and six degrees of freedom are available. One degree of freedom is used to control the magnitude of the fundamental voltage and the remaining five degrees of freedom are used to eliminate 3^{rd}, 5^{th}, 7^{th}, 9^{th} and 11^{th} order harmonic components as they dominate the total harmonic distortion. As shown in Fig. 6, the percentage of harmonic order 3^{rd}, 5^{th}, 7^{th}, 9^{th} and 11^{th} is less than 0.5% and the THD is around 9%.

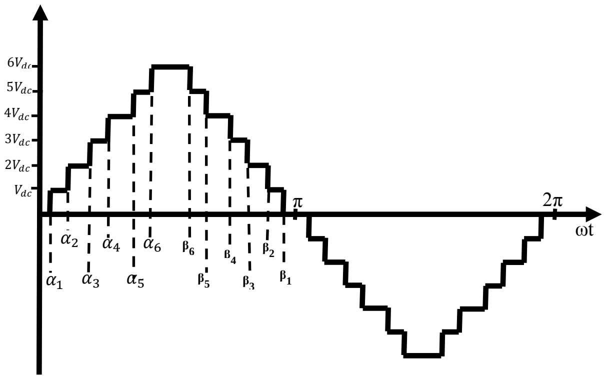


Figure5: Output phase voltage waveform for 13-level MLDC.

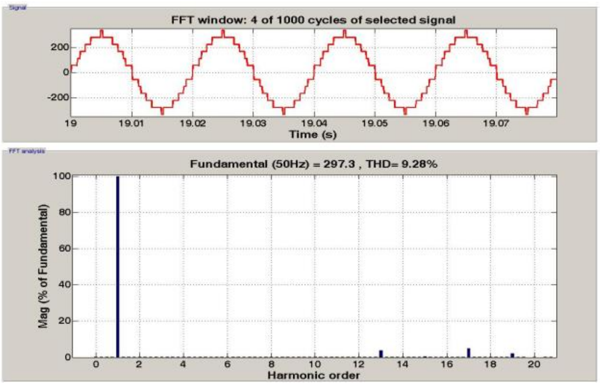


Figure6: Phase voltage of 13-level MLDC with corresponding FFT.

3.2 Complexity and efficiency

One of the most obvious disadvantages of any power electronic converter is the numerous of power semiconductor switches [8]. Every switch requires a gate driver circuit, therefore, increasing the complexity and size of the overall circuit. The requirement of a multiple gate driver circuit increases the total cost. As a consequence, in practical applications, a reduction of the used switches is crucial. Therefore, this paper demonstrates the comparison study of three popular multi-level DC/DC converters as shown in Fig. 4. Besides, all these topologies are simulated to assess the quality of AC power for reducing the percentage of harmonics, and to compute the power loss of each topology. For the first part, Fig. 6 shows that the percentage of THD is around 9% and the percentage of each order of harmonic is less than 0.5%. It means that the SHE technique gives good solution to achieve a minimum THD. The main target of this part is to decide which topology can be used for the battery system. Since the efficiency of each topology depends on the amount of the electric power flow from the battery system (DC side) to the electric load (AC side). Therefore, Table 2 shows the number of switches and diodes of each topology. One can observe that topology 3 has a minimum number of switches, and topology 2 has a minimum number of diodes. Since the gate drivers are required only for switches, the topology 3 reduces the installation area, gate drivers needed and the cost of the whole setup due to the minimum number of switches.

3.2.1 Simulation results

In order to compare the characteristics of these topologies, the models of these topologies have been simulated in MATLAB/SIMULINK environment. These simulations are carried out on a single-phase resistive load. To assess the efficiency of each topology, six battery modules are used, whereby each module has 16 cells (Lithium-ion iron phosphate battery with rated capacity of 7Ah), and the total voltage of each module is 56 volts. In addition, four cases are used for loading: 1) 52 Ω (1 KW), 2) 10.5 Ω (5 KW), 3) 5 Ω (10.5 KW), 4) 2.5 Ω (20 KW).

Table2: Number of switches and diodes of each topology

	Topology1	Topology2	Topology3
Number of switches	16	15	10
Number of diodes	16	15	16

From Fig. 7, Fig 8, Table3 and Table 4, one can observe that topology 3 can achieve a minimum power loss and a high efficiency compared to other topologies.

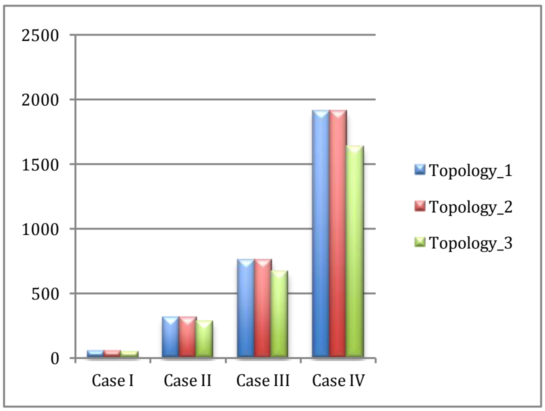


Figure7: Power loss of topologies.

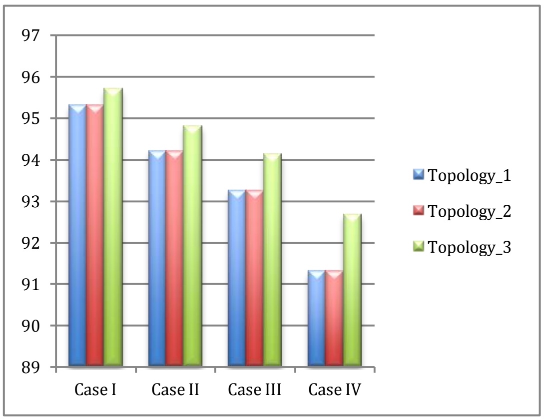


Figure8: Efficiency of topologies.

Table3: Power loss of topologies

Power loss (W)	Topology1	Topology2	Topology3
Case I	51,77	51,77	47,524
Case II	312,31	312,31	280,33
Case III	756,42	756,43	666,36
Case IV	1908,63	1908,63	1635,62

Table4: Efficiency of topologies

Efficiency (%)	Topology1	Topology2	Topology3
Case I	95,3	95,3	95,7
Case II	94,2	94,2	94,8
Case III	93,25	93,25	94,11
Case IV	91,3	91,3	92,66

In addition, the power loss and the efficiency of topology 1 and topology 2 are almost equal. Although, topology 2 has a lower number of switches and diodes compared to topology 1. As shown in Fig. 4, the difference between topology 1 and topology 2 is that the first vertical switch and diode are removed from topology 1 to configure topology 2. Therefore, topology 2 reduces the complexity compared to topology 2.. However, from the point of view of efficiency, topology 1 and topology 2 have the same efficiency at different power loads as shown in Table 3 and Table 4.

3.3 Fault-tolerance and the percentage of continuity

Battery module failure or switching device failure is often a cause of circuit dysfunction. Many factors can lead to a power switch failure or a battery module failure [8]. Toward the end of the battery life in the vehicle, the energy capacity left in the battery is not sufficient to provide the designed range for the vehicle. Typically, the automotive manufacturers recommend battery replacement when the remaining energy capacity reaches 70%–80% of rated capacity [1]. There is still sufficient power (kilowatts) and capacity (ampere- hour) left in the battery to support various grid applications. However, one can observe that used batteries are exposed to failure during the operation [2]. As shown in Fig. 4, each battery module is connected to two switching units, one of them is vertical and the other is horizontal. For topology 1, two switches with anti-parallel diodes are connected to each battery module. Therefore, the vertical diode can be used as a short circuit across the battery modules to disconnect any battery module if it is failed. Furthermore, the voltage level of topology 1 can change from 13-level to 11-level or 9-level or 7-level based on the health of each battery module. For topology 2, it is like topology 1 except that the first module cannot be disconnected because the vertical switch and diode of first module are removed to minimize the numbers of power semiconductor devices. For topology 3, all vertical switches are removed, however all vertical diodes are still in the circuit. These diodes are used to produce a short circuit across any battery module where any horizontal switch is turned off during the normal operation or in case of a battery module failure. As shown in Table 5, the case study which is used to compare the three topologies is four converters level from six modules (from 7-level to 13-level and ignore two levels 5-level and 3-level). As a result, one can observe that the percentage of topology service continuity of topology 1 and topology 3 is the same and higher than the service continuity of topology 2. Table 5 shows all available probabilities in case of battery module failure for each topology; the total probability is 64 (for six modules). As a consequence, topology 2 represents a less percentage of continuity due to the removal of the first vertical switching unit.

3.4 The possibility of loading

As previously mentioned, three different popular MLDC structures have been applied in literature [19-21]. Three types of the electric load are used for simulation: 1) R-load, 2) R-L load and 3) R-L-C load. As shown from the simulation results, Table 6 demonstrates the possibility of loading of each topology. In [21] topology 3 is used to connect photovoltaic (PV) sources to resistance load. However, topology 3 cannot be used to connect battery modules to the electric load, which has an inductance or/and capacitance load. An inductance load produces a high-voltage peak at the beginning of each half cycle of output voltage as shown in Fig. 9. From Fig. 9, the voltage peak leads to increase the THD to be around 19% instead of around 9%. Therefore, Topology 3 can be only used to connect the series DC sources (battery modules) to a resistive load.

Table5: The percentage of continuity of each topology

Percentage of continuity	7 level	9 level	11 level	13 level	%
Topology1	20	15	6	1	66
Topology2	10	10	5	1	41
Topology3	20	15	6	1	66

Table6: The possibility of loading

	R-load	RL-load	RLC-load
Topology1	Valid	Valid	Valid
Topology2	Valid	Valid	Valid
Topology3	Valid	Not valid	Not valid

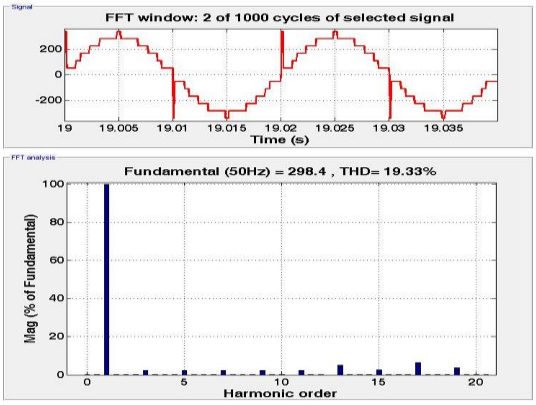


Figure9: Phase voltage of topology 3 (R-L load) with corresponding FFT.

4 Conclusion

This paper represents a comparative study of the most popular multilevel DC/DC converters that can be used for the second life battery applications. These topologies have been analyzed, and their performance characteristics have been presented. The response of each topology has been verified at different load types (such as R, R-L, and R-L-C loads). A selected harmonic elimination (SHE) technique is used to realize the control system of the multilevel DC/DC converter, and its influence on the performance of each battery module is analyzed. Finally, the results have demonstrated that Topologies 1 & 3 have the same percentage of continuity (66%) compared to the Topology 2 (41%). Furthermore, Topology 3 can provide a high efficiency, high reliability, low price and simplicity. However, this topology cannot be used to feed both R-L and R-L-C load due to the influence of the discharge current of the inductance load. Therefore, it can be expected that this study can be utilized for development of a new topology of DC/DC multilevel converter to modify topology 3 to overcome their disadvantages.

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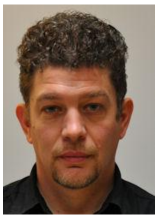
Authors

Mohamed Abdel Monem was born in Cairo, Egypt, in 1982. He received the B.Sc. and M.Sc. degrees in Electrical Engineering from Helwan University, Cairo, Egypt, where he is currently working toward the Ph.D. degree in the Department of Electrical Engineering and Energy Technology (ETEC), Vrije Universiteit Brussel (VUB), Belgium. His current research interests include Second-Life Batteries, Battery Aging and Characterization, Systems Modelling, Parameter Estimation, Power Electronics, Renewable Energy, Control Systems and Battery Management System.

Dr. Ir. Omar Hegazy (M’09) was born in Cairo, Egypt, in 1978. He received the B.Sc. (Hons.) and M.Sc. degrees in electrical engineering from Helwan University, Cairo and the Ph.D. degree (with the greatest distinction) from the Department of Electrical Machines and Power Engineering (ETEC), Vrije Universiteit Brussel (VUB), Brussels, Belgium, in July 2012. He is currently a Postdoctoral Fellow at ETEC and MOBI team at VUB. He is the author of more than 40 scientific publications. He is a member of IEC standards for wireless power transfer systems. Currently, he is involved in different FP7 projects (such as Safedrive and Unplugged). His current research interests include power electronics, drive systems, electric vehicles, (plug-in) hybrid electric vehicles, power management strategies, battery management systems, renewable energy, control systems, and optimization techniques.

Noshin Omar was born in Kurdistan, in 1982. He obtained the M.S. degree in Electronics and Mechanics from Erasmus University College Brussels and PhD degree in the department of Electrical Engineering and Energy Technology ETEC, at the Vrije Universitit Brussel, Belgium. He is currently team leader of the Rechargeable Energy Storage System group of the Vrije Universiteit Brussel. His research interests include applications of BEV’s/HEV’s/PHEV’s, electrical modeling, thermal modeling, lifetime modeling of electrical-double layer capacitors, batteries and hybrid capacitors. He is also active in several international standardization committees such as IEC TC21/22.



Bart Mantels is a project responsible at the Flemish technological institute VITO in the unit Energy Technology. He is in charge of the domain of electric active components for grid governance, closely related to electric energy storage and power electronics. He graduated in Computer Science (Katholieke Universiteit Leuven, 1996). He worked in several companies as team manager before joining the smart grid activities of VITO in 2012. He is qualified for the Six sigma design and also a certified marketing manager.

Grietus Mulder is a researcher at the Flemish technological institute VITO in the unit Energy Technology. He is specialist in the field of electric storage for automotive and renewable energy applications. He graduated in Applied Physics (University Twente, The Netherlands, 1997).He develops battery testing methods for automotive applications like plug-in hybrid vehicles and also for the integration of photovoltaic energy in a smart grid network. His main interest is on system integration with electricity storage as central component. He is (co)author of 15 peer-reviewed publications.

Peter Van den Bossche graduated as civil mechanical-electrotechnical engineer from the Vrije Universiteit Brussel and defended his PhD at the same institution with the thesis "The Electric Vehicle: raising the standards". He is currently lecturer at the engineering faculties of the Vrije Universiteit Brussel, and in charge of co-ordinating research and demonstration projects for electric vehicles in collaboration with the international associations CITELEC and AVERE. His main research interest is electric vehicle standardization, in which quality he is involved in international standards committees such as IEC TC69, of which he is Secretary, and ISO TC22 SC21.

Prof. Dr. Ir. Joeri Van Mierlo (IEEE: M’06 & SM’12) received the Ph.D. degree in electromechanical engineering sciences from the Vrije Universiteit Brussel, Brussels, Belgium, in 2000. He is currently a Full-Time Professor at this university, where he leads the MOBI— Mobility and Automotive Technology Research Centre (http://mobi.vub.ac.be). Currently, his activities are devoted to the development of hybrid propulsion (power converters, energy storage, energy management, etc.) systems as well as to the environmental comparison of vehicles with different kind of drive trains and fuels (LCA, WTW). He is the author of more than 200 scientific publications. He chairs the EPE chapter “Hybrid and electric vehicles” (www.epe-association.org); he is the Secretary of the Board of the Belgian Section of AVERE (ASBE) (www.asbe.be) and is the Vice-President of AVERE (www.avere.org). He is Editor In Chief of the World Electric Vehicle Journal Volume 3 and Co-Editor of the Journal of Asian Electric Vehicles. He is an active member of EARPA—the European Automotive Research Partner Association. Furthermore, he is a member of EGVIA. He was the Chairman of the International Program Committee of the International Electric, Hybrid and Fuel Cell Symposium (EVS24).