Reconfigurable Cascaded Multilevel Converter design for Battery Energy System Storage

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***Abstract*—This paper presents the Reconfigurable Cascaded Multilevel converter employed for battery energy storage systems. The main advantage lies on the possibility to fully control each battery cell, improving the overall performances of the storage system. Indeed, the Reconfigurable Cascaded Multilevel Converter is compared with a CHB grid tie converter and two-level inverter, in terms of filter design, power losses and battery losses. The analysis results show that, under the same operative condition, the inductive filter required is at least 70% less than the other two topologies. Moreover, the RCMC provides the highest converter efficiency in all operative conditions.**

Keywords*—BESS, Cascaded H-Bridge, Efficiency, Multilevel converters, Reconfigurable Cascaded Multilevel converter, Two-level inverter.

I. INTRODUCTION

Battery energy storage system (BESS) has become a fundamental component for the integration of renewable sources in the grid. Indeed, energy generated from photovoltaics and wind-turbine generators may be intermittent, creating undesired effects on voltage and frequency grid. Therefore, energy storage systems are usually installed close to renewable energy source to solve the consequent power-quality issues [1].

Initially, storage systems consisted in a unique battery pack whose voltage was converted in AC and then stepped up to the grid voltage to be connected. This structure presented the main disadvantages to be expensive – the step-up transformer costs are significant - and not efficient in terms of battery utilization. As it is now well-known, the serial connection of high number of battery cells may limit the overall operation of the battery pack [2]. Furthermore, the more are the battery cells connected, the less is the whole reliability: one faulty cell can provoke the damage of the overall battery pack.

Therefore, in the last years, the majority of BESS have been realized with multilevel converter topologies [3]-[5]. More specifically, the most used is the Cascaded H-Bridge (CHB), which permits different advantages. The storage system is divided in different battery packs, which are inter-connected and controlled by single H-Bridge converters. The structure composed by battery pack with its own H-Bridge is called submodule; the submodules are connected in series. The modular structure, then, allows to avoid the interface step-up transformer between the grid and the converter, to reduce the switching frequency and to obtain high quality output voltage waveform. Moreover, the CHB structure fits completely the BESS application thanks to the possibility to fully control the battery unit within one submodule, enhancing the fault tolerant and the implementation of balancing schemes, without the need of extra components.

Meanwhile, literature studies have investigated and highlighted the importance to fully control single battery cells or, in general, to minimize the serial connections. The advantages would be tremendous: the storage system performances would be not limited by the weakest cells, the balancing could be performed always in active way – without the utilization of dissipative battery management systems (BMSs) – and, in case of fault, the operation could continue by isolating the damaged part. Since the batteries represents the 30%-50% of the cost of the overall structure, improving the management of the storage system would mean a significant saving. Considering that the batteries employed for BESS application are usually reconditioned from a previous application, the necessity to efficiently manage their life cycle and operation acquires even more importance.

On the other hand, the distributed structure of the CHB still does not allow to access single battery cells. Specifically, implementing a converter where each battery cell has its converter means having a tremendous number of switches and an increased rate of power losses. Therefore, intelligent battery packs (IBPs) started to be considered as alternative in storage applications [2],[6]. The serial and parallel connections within one battery pack are characterized by a combination of switches which allow to fully control each cell.

This paper presents a Reconfigurable Cascaded Multilevel (RCMC) converter for BESS application. The RCMC structure resembles the multilevel converter but permits the full control of each battery cell, thanks to the Reconfigurable battery modules (RBMs) [7]. This topology enhances all the potential advantages described above.

This paper is structured as it follows. In the second section, the converter structure and the implemented controls are discussed. The third section compares the RCMC with a two-level inverter and a CHB, analyzing the filter design, power losses and battery losses. The fourth section concludes the paper.

II. RECONFIGURABLE CASCADED MULTILEVEL CONVERTER FOR BESS APPLICATION

A. Converter structure

The RCMC structure is shown in Fig.1. Several submodules are serially connected; each of them is characterized by the serial connection of RBMs connected to a H-Bridge converter, used to invert the output voltage and to bypass the submodules . Each RBM includes three battery cells - a larger number would create short circuits between the cells [7].

The functionality which makes the RCMC extremely promising for the BESS application is the full control of the battery cells. Through different paths, the switches within one RBM permits to access the cells singularly or in groups. In this way, the SOC balancing of battery units is performed during normal operation without the need of extra time and extra components. Moreover, the modular structure enhances the fault tolerant operations, allowing the disconnection of one RBM or an entire submodule, according to the damage entity and the wanted safety level.

The structure of the RCMC can be decided according to customizable requirements. In this paper, the configuration with 3 RBMs per each submodule is chosen [7]. On the other hand, the peak voltage installed within one phase is designed according to the voltage ratings of the AC grid to which the BESS will be connected. In this paper, a low voltage grid tie converter is analyzed, therefore the peak phase voltage of the RCMC must be:

$$\hat{V}_{RCMC\_ph} = \sqrt{2} \cdot 230\ V = 325\ V \qquad (1)$$

Assuming to use 3.2 V-LiFePo4, whose minimum voltage is equal to 2.8 V, the overall number of RBMs is:

$$N_{RBM} = \frac{\hat{V}_{RCMC\_ph}}{3 \cdot V_{batt\_min}} = \frac{325\ V}{3 \cdot 2.8V} = 39 \qquad (2)$$

Where 3 is the number of battery cells in each RBM. Therefore, the total number of submodules per phase is equal to:

$$N_{SM} = \frac{N_{RBM}}{3} = \frac{39}{3} = 13. \qquad (3)$$

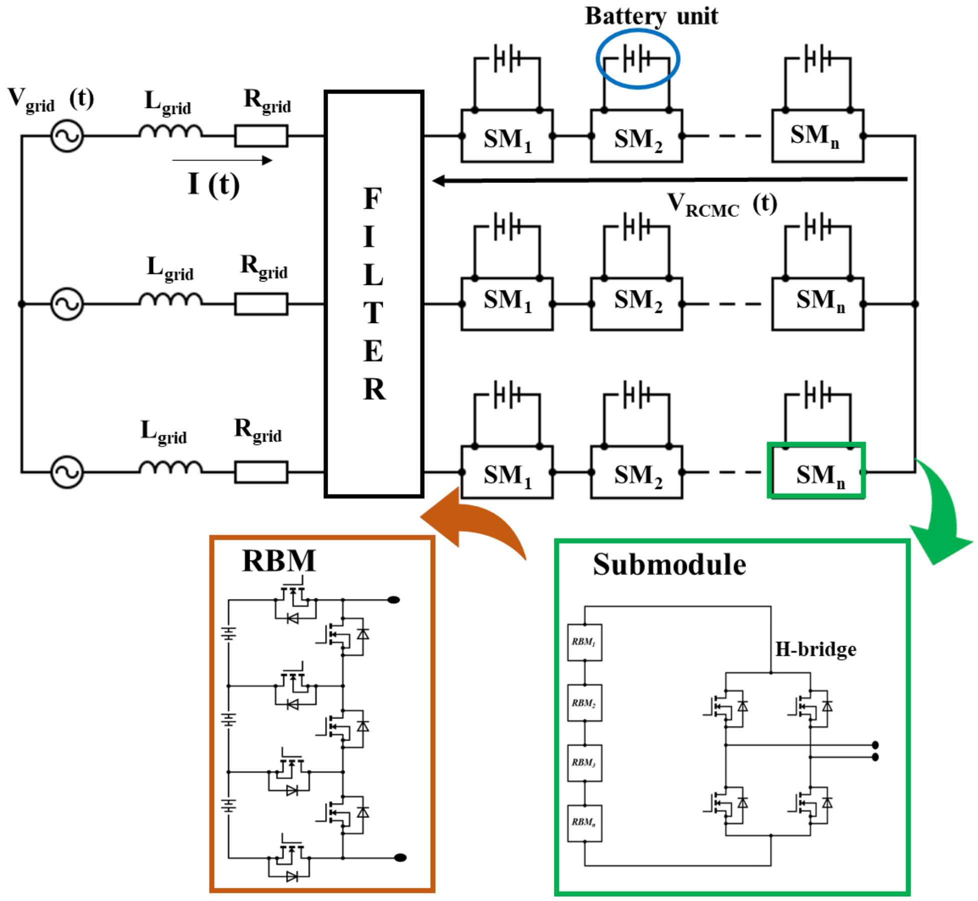

Figure 1 – Reconfigurable Cascaded Multilevel Converter. The RBM and submodule structures are shown in the orange and green squares, respectively.

B. *Control strategies*

The control strategy requested for a converter used in BESS application should implement a power control which operates on top level, to supply the power fluctuations of the grid, and on local level, to guarantee the state of charge (SOC) balancing of the battery cells. Indeed, particular working conditions may affect the capacity of the battery units and it is important to compensate the differences between them through an accurate control [7]. Therefore, a power control loop is combined with a sorting strategy in order to provide or absorb power keeping the system balanced. Fig.2 shows the battery cells voltages in absorption and delivering phases, when the active power exchanged is assumed, by convention, positive and negative, respectively.

The power control is implemented by modulating the converter with the Nearest Level Modulation. Indeed, the high number of levels of the RCMC, equal to 235 [7], permits to have a negligible harmonic content in the output current even with low values of filter inductance. Further details will be given in the next section.

III. COMPARISON WITH TWO-LEVEL INVERTER AND CHB

The RCMC is compared with a two-level inverter and a CHB grid tie, described in [9]. Table I summarizes the key features of the converters and system simulated.

A. *Filter Design*

The filter inductance is designed according to the current ripple method. According to [9], the CHB and the two-level inverter need an inductive filter of 3.9 mH and 6.4 mH, assuming a current value equal to 36 A and allowing a 5% of maximum current ripple. The inductive filter calculated for the RCMC is equal to 1.2 mH, which is 70% and 80% smaller than the two-level inverter and CHB, respectively.

Moreover, the quality of the output power quality results to be extremely high even for low values of current. Fig.3 shows the current waveforms for the RCMC, CHB and two-level inverter for the 10% of the nominal operative conditions. The RCMC guarantees the lowest THD in both conditions, even with the lowest inductive filter and switching frequency.

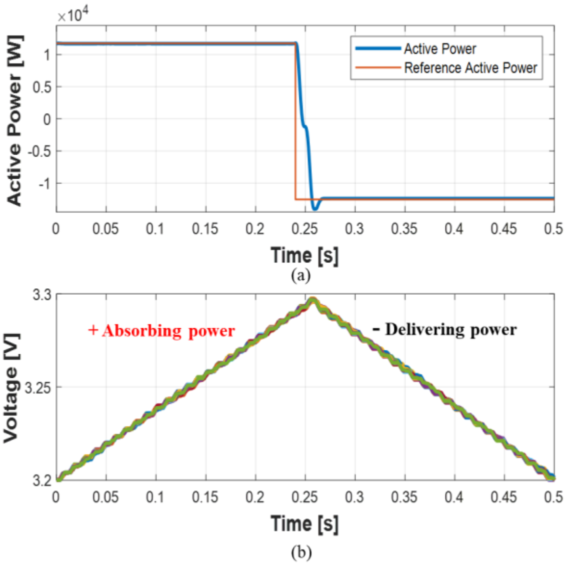

Figure 2 – (a) Reference active power signal vs real active power. (b) Voltage battery cells when the converter is required to absorb power and to deliver power, respectively.

TABLE I. SYSTEM AND CONVERTERS PARAMETERS

System parameters	
Grid Line to line voltage	400 V
Nominal current rms	51.96 A
Maximal battery voltage LiFePo4	3.6 V
Two- level inverter	
Maximal DC link voltage	750 V
# LiFePo4 battery cells	750/3.6=208
IGBT devices	FS100R12KT4G
Modulation	PWM
Switching frequency	8 kHz
CHB	
Maximal battery unit voltage	57.7 V
# LiFePo4 battery cells per unit	57.7/3.6=16
# submodules per phase	8
Mosfet devices	IPB036N12N3GATMA1
Modulation	Phase Shift PWM
Switching frequency	1 kHz
RCMC	
Maximal battery unit voltage	3.6 V
# LiFePo4 battery cells per phase	117
Mosfet device for RBM	IPT004N03LATMA1
Mosfet device for H-bridge	NTMTS0D7N06CLTXG
Modulation	Nearest Level

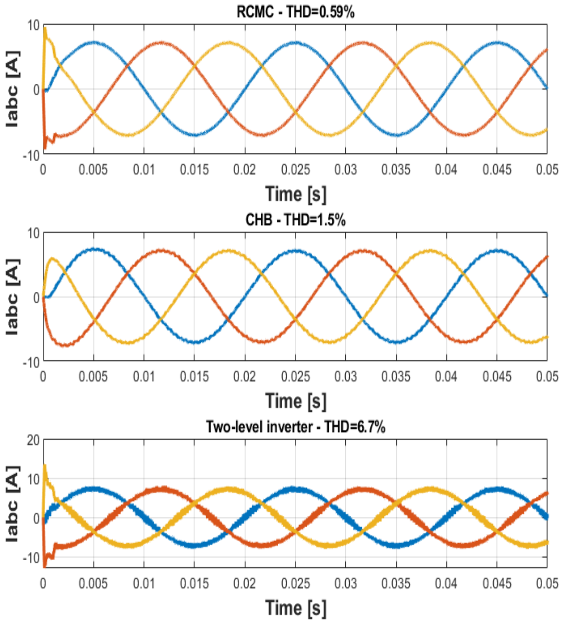

Figure 3- Current waveforms for the 10% of the nominal operative conditions. The RCMC provides the lowest THD.

B. *Power losses comparison*

The three converters are compared in terms of power losses, which are composed by converter and battery losses. The first ones are the result of the sum of conduction and switching losses. The second ones are due to the internal resistance of each battery cell. For BESS application, where battery cells work with a low value of C-rate, it is acceptable to assume that each battery cell has the same internal resistance, as stated in [2]. Assuming to have only one parallel string, battery losses can be written as:

$$P_{batt} = N_s R_{int} I_{rms}^2 \tag{4}$$

Where N_s is the number of cells connected in series within the battery pack, R_{int} is the internal resistance of each cell and I_{rms}^2 is the current flowing through the cells. The calculation method of the power losses for the three converters is described in the following.

1) *Two-level inverter*

Conduction and switching losses of FS100R12KT4G are evaluated with the software IPOSIM [10].

The battery losses can be calculated with (4), placing N_s equal to 208.

2) *CHB*

Switching losses are computed with PLECS, by modelling the thermal behaviour through the datasheet parameters [10]. Conduction losses can be written as:

$$P_{cond\_CHB} = 3 \cdot 2 \cdot N_{SM} \cdot R_{dson} \cdot I_{rms}^2 \tag{5}$$

Where 3 is the number of the converter phases, 2 is the number of switches always in conduction, N_{SM} is the number of submodules per phase and R_{dson} is the internal resistance of the MOSFETs.

The battery losses cannot be calculated directly as in the two-level inverter. In the CHB, indeed, the battery units crossed by the flowing current depends on the number of active submodules in each moment. Therefore, battery losses must be computed by evaluating the instantaneous values of active submodules and current. The sum of the instantaneous contribution of the battery losses are then averaged on a period of the output fundamental frequency. Discretizing the computation, the battery losses can be written as:

$$P_{batt\_HB} = \frac{1}{k}\sum_{i=1}^{k} N_{SM}(i) \cdot N_s \cdot R_{int} \cdot I(i)^2 = \frac{1}{k}\sum_{i=1}^{k} N_{batt}(i) \cdot N_s \cdot R_{int} \cdot I(i)^2 \tag{6}$$

where k is the number of intervals in which is divided one period of fundamental frequency and N_s is the number of cells connected in one battery module.

3) *RCMC*

Switching losses can be neglected and conduction losses are calculated as stated in [7]. Battery losses – as for the CHB – are computed by evaluating the instantaneous number of active battery cells within the RBMs and current values– and then, averaged on a period of the output fundamental frequency. The battery losses can be still written as:

$$P_{batt\_RCMC} = \frac{1}{k}\sum_{i=1}^{k} N_{batt}(i) \cdot R_{int} \cdot I(i)^2 \tag{7}$$

IV. DISCUSSION RESULTS

Fig. 4, Fig.5 and Fig.6 shows the converters, batteries and overall systems efficiencies respectively.

Fig.4 shows that the two-level inverter has the largest power losses, but its efficiency increases with increasing power of the operative conditions. The CHB and the RCMC, instead, show a decreasing efficiency trend: the more is the power, the more is the current flowing in the power electronics converter. The two converters show comparable efficiency values, but the RCMC appears to be the most efficient for all operative conditions.

Fig.5 confirms the worst performance for the two-level inverter. The losses are significant because the fixed structure of the battery pack forces the load current to flow in each cell. Therefore, the higher is the current, the higher are the losses due to the internal resistance of each battery cell. On the other hand, the modular structure of the multilevel converters allows to activate only the necessary battery modules or cells, for the CHB and the RCMC, respectively, reducing the overall battery losses. Finally, the CHB has the highest efficiency, followed by the RCMC, whose efficiency decreases with the increase of the current.

Fig.6 shows the overall system efficiency. The two-level inverter has the lowest efficiency, while the two multilevel converters have similar behaviour. The RCMC is more efficient for the lower current values, while the CHB reaches the top position for the highest values.

Fig.7 shows the three efficiency curves along the entire power spectrum. The three curves decrease proportionally to the power. This behaviour is well-known for the two multilevel converters, for which more submodules are activated at higher power ratings . On the other hand, the two-level inverter is more performant for high power operative conditions, but its overall inverter efficiency trend is strongly affected by the significant battery losses, which determine the descendent trend.

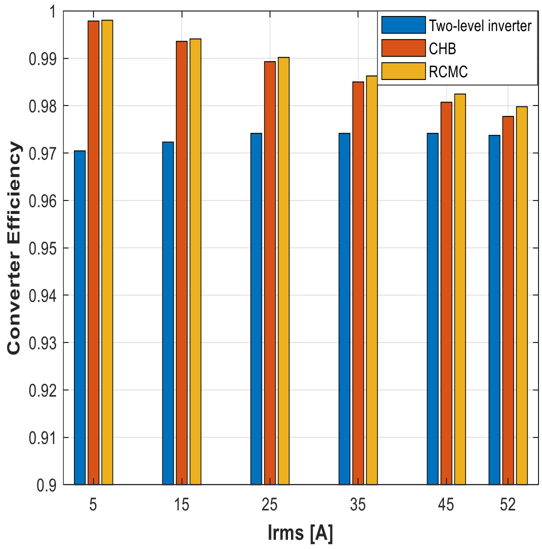

Figure 4 – Comparison between converters efficiencies.

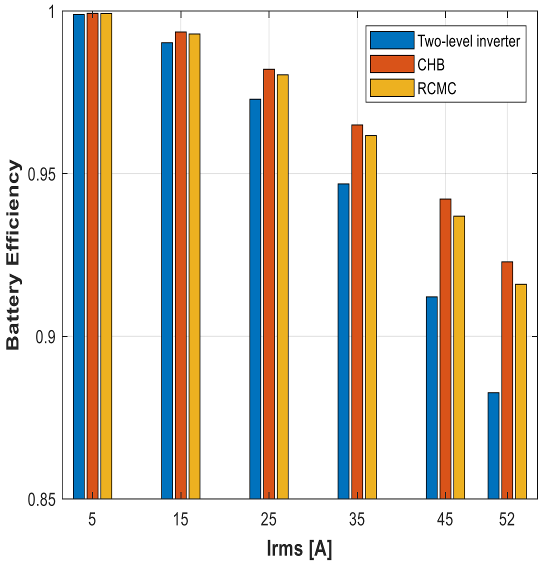

Figure 5 – Comparison between batteries efficiencies.

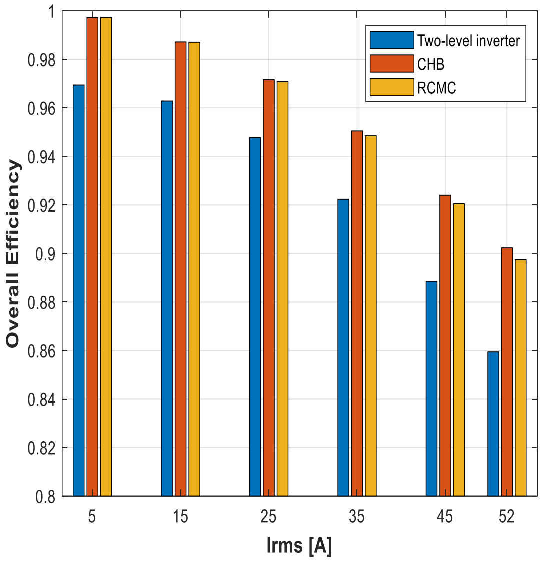

Figure 6 – Comparison between overall systems efficiencies.

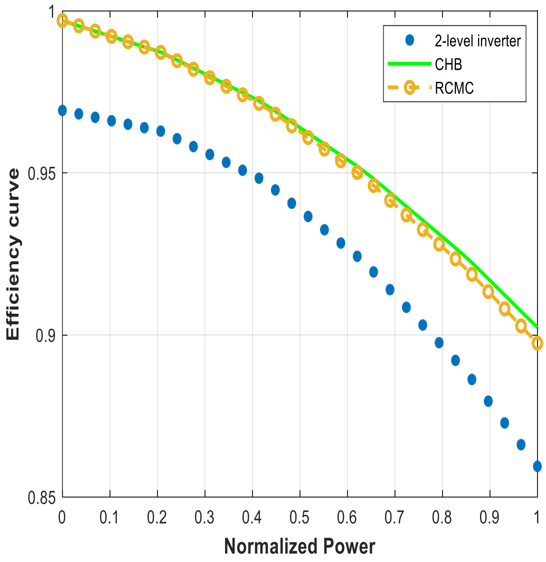

Figure 7 – Efficiency curve on the normalized power.

V. CONCLUSIONS

This paper proposes the Reconfigurable Cascaded Multilevel Converters for BESS application. The structure is here presented and compared with the conventional topologies used for storage systems, the two-level inverter and the CHB. The results confirms that the RCMC is widely more efficient than the two – level inverter and comparable with the CHB performances.

These results confirm the feasibility of the RCMC; the structure complexity does not affect the performances and allows, on the contrary of the other two topologies, to better manage the battery cells and move a step forward to the intelligent battery pack.

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