Reconfigurable Cascaded Multilevel Converter: A New Topology For EV Powertrain

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***Abstract*—This paper presents a novel cascaded multilevel converter topology with reconfigurable battery modules able to merge the power conversion and the battery management functionalities for electric powertrain application. In the proposed topology, each battery cell can be individually connected or bypassed according to the required voltage and current levels. Both the charging and discharging processes can be controlled to avoid voltage imbalances between the cells and to enhance fault tolerance, battery life, and safety. Converter switching and conduction losses are evaluated and used as key parameters for the optimization of the proposed architecture. Furthermore, an efficiency comparison between a conventional three-phase IGBT-based inverter and the proposed topology is carried out. The two topologies are evaluated according to the WLTP Class 3 driving cycles, showing their average efficiency in each cycle. The comparison results show that the performance achieved with the proposed topology is extremely promising to combine state-of-the-art functionalities with the new paradigm of battery management**.

Keywords—Comparison, driving cycles, efficiency, inverter, multilevel converter, new topology, reconfigurable battery modules.

I. INTRODUCTION

In conventional battery electric vehicle (BEV) drivetrains, the battery cells are usually interconnected to form a fixed structure, also known as battery pack, designed according to the inverter voltage and current ratings. This configuration, where the battery pack supplies the dc-link voltage of an IGBT-based three-phase inverter, is today the common choice for commercial drivetrains, since it manages to achieve quite high inverter efficiencies at rated and peak load. However, it has been known to suffer drastic efficiency drops during operation at partial load [1], [2]. Furthermore, in conventional configurations, the proper operation of the battery pack requires the use of an external passive or active Battery Management System (BMS) to balance the State of Charge (SOC) of each cell. Although advanced BMS solutions have been developed, this configuration still suffers from cell voltage imbalance issues, so that the overall performance of the pack is limited by the less charged cells [3]. Consequently, conventional inverter-based drivetrains present disadvantages during both the motoring and the charging phases.

In this scenario, recent published research works have proposed the integration of the battery cells and the converter into a single system to achieve the merging of the power transfer and battery management functionalities, higher system compactness, increased flexibility in the optimization of the system operation, and better performance during different working cycles. Multilevel converters are the ideal candidate to fully exploit this new concept because of their modular structure. Their application in BEV drivetrains, however, significantly changes the architecture of the battery packs and, eventually, the BMS concept itself. Since in these new configurations the battery cells are distributed among an increased number of submodules per phase, it is possible to develop advanced control strategies to keep the battery packs balanced during the motoring phase. In particular, in [4] and [5] a Modular Multilevel Converter (MMC) is proposed emphasizing the benefits for battery balancing and SOC management: the authors developed an algorithm able to reach in few minutes the same SOC state for each battery cell.

In [6], a comparison between two conventional three-phase inverters, one employing IGBTs and the other built with SiC MOSFETs, and a Cascaded H-Bridge (CHB) is performed. The conclusions reached by the authors highlight the convenience in using a multilevel converter for automotive application mainly due to cost, efficiency, and energy density considerations. The CHB converter [6]-[8] and one of its variants, the so-called Hybrid-Cascaded Multilevel Converter (HCMC) proposed in [9], have been regarded as valid candidates for automotive applications under efficiency and costs aspects. However, the possibility of using a single converter submodule for each battery cell has been very rarely considered because of the high number of switches required, which consequently leads to very large conduction losses. Indeed, in [10] the best number of submodules per phase is found to be between 3 and 4.

The main contribution of this work is to demonstrate the feasibility of using a multilevel converter for electric vehicle application to directly control the charge and discharge of each single cell of the battery pack (i.e., acting also as BMS) without compromising system efficiency and costs. To this purpose, this paper presents a novel Reconfigurable Cascaded Multilevel Converter (RCMC) topology that integrates the battery cells directly within the converter via Reconfigurable Battery Modules (RBMs). The proposed RCMC exploits its modular structure to perform the dynamic control of the battery cells, guaranteeing a balanced battery operation in all the operating conditions. During the discharging phase, the dynamic control of Reconfigurable Battery Modules (RBMs) fully exploits the battery cell capacity to power the load without being limited by the weakest cells. While charging the battery, different switch configurations can be implemented to fully charge all battery cells without any limitation due to SOC imbalances. Finally, cell faults can be easily detected and isolated by disconnecting the damaged parts. In conclusion, the capability of managing each single battery cells may lead to an increase of battery lifetime, system efficiency and safety.

The paper is structured as follows: the novel RCMC topology and its operation are presented in Section II, converter losses are evaluated in Section III to find the optimal configuration for the RCMC modules and the comparisons with the conventional three-phase IGBT inverter are carried out in Section IV and V. Finally, conclusions are drawn in Section VI.

II. Description of the Proposed Topology

The proposed RCMC topology is depicted in Fig. 1a. Different submodules (SMs) are connected in series for each phase to obtain the whole converter structure. The structure of each SM is detailed in Fig. 1b: the battery cells are organised in different RBMs, whose output voltage works as the dc-link for a single H-bridge converter. The H-bridge converter is only used at the fundamental frequency to invert the voltage polarity of the SM. The innovative part of the proposed topology is the RBM itself. In each RBM, in fact, three battery cells are interconnected through a combination of power switches so that it is possible to flexibly insert or bypass one cell at a time, depending on load requirements and cell SOC. A larger number of RBMs may be connected in series to increase the voltage of a single SM, as will be discussed in detail Section III.

A. RBMs operation

The three battery cells in one RBM can be individually activated according to the desired voltage or/and SOC values, avoiding undesired voltage imbalances during charging and discharging phases. Depending on the number of cells that need to be connected and on their position within the RBMs, the conduction path may involve a different number of switches. Larger is the number of cells activated, smaller is the number of conducting switches: four switches must be on to connect one battery cell, three switches to connect two cells or bypass all of them, and two switches to connect all three cells. Compared to other multilevel configurations, the proposed RCMC permits to reduce conduction losses when all cells are connected. Fig. 2 shows the seven possible combinations to insert and bypass the battery cells in one RBM.

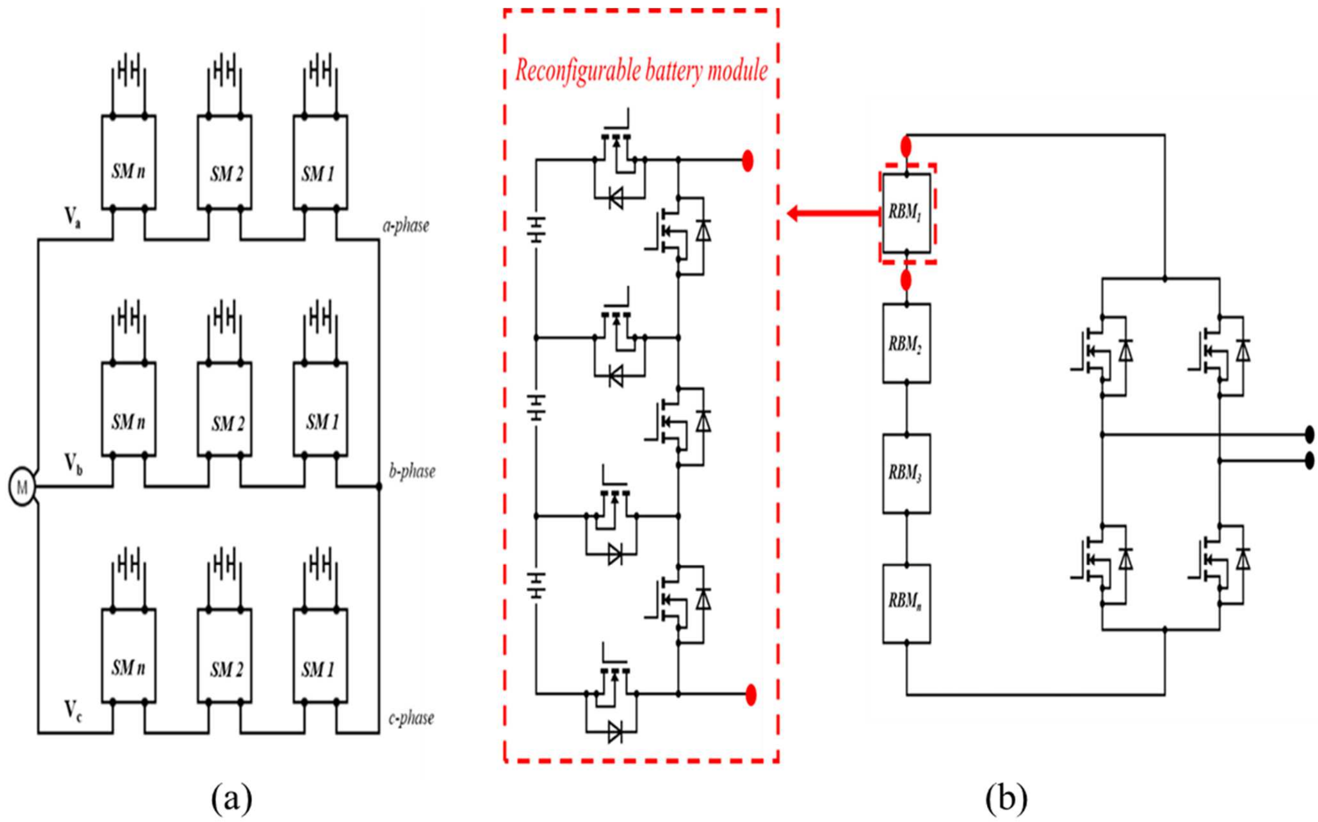
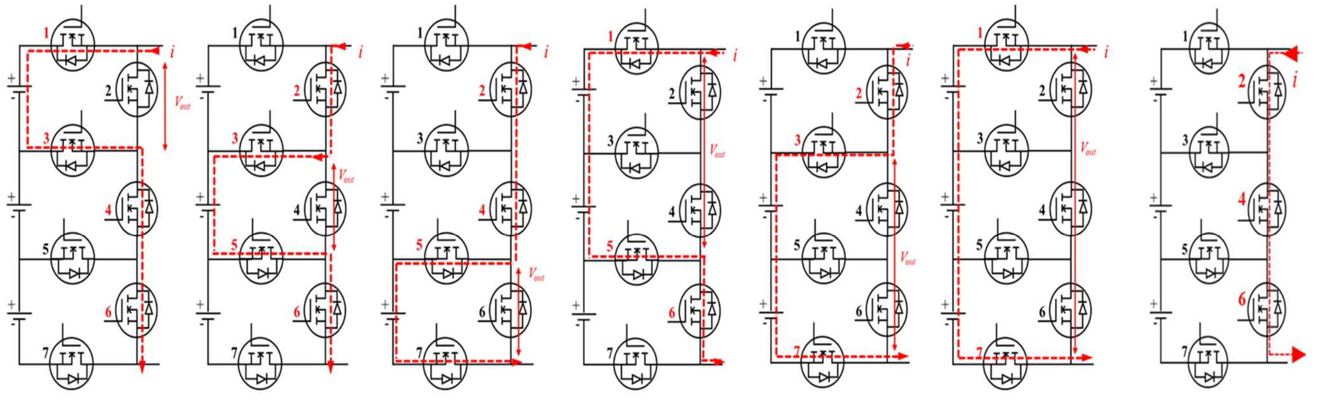


Figure 1 – Proposed RCMC topology (a) and internal structure of each submodule with a detail of the RBM architecture, in red (b).



(a) (b) (c) (d)

Figure 2 - Combinations for battery cells insertion: (a) One cell connected, (b) two cells connected, (c) three cells connected. (d) The RBM is bypasses, no cell is connected.

In case two battery cells need to be inserted, they cannot be the first and the third: with reference to Fig. 2, the switches 1,3,4,5 and 7 cannot be in conduction at the same time to not short out the battery cell in second position. For the same reason is not feasible to increase the number of battery cells in one RBM: for a higher number of battery cells, the flexible insertion of one or more of them would cause circulating currents inside the converter and shorting out occurrences.

Finally, the RBM here proposed has not only the suitable structure for flexible battery cells insertion but also to implement fault tolerance strategies in a hierarchical way. If one or more battery cells show a faulty behaviour, the full control of the topology allows to disable the battery cells itself or the entire submodule. In this way, the modular structure of the converter is able to guarantee a continuous operation without compromising the overall functionalities of the drivetrain.

III. RCMC PERFORMANCE ANALYSIS

The performance analysis of the proposed RCMC is carried out by evaluating the switching and conduction losses via simulation. A three-phase surface-mounted Permanent Magnet Synchronous Motor (PMSM) is considered in this analysis for simplicity, since the detailed control of the machine is outside the scope of this paper. The PMSM torque-speed characteristic according to commercial BEVs is shown in Fig. 3, while its parameters are listed in Table I.

A. Estimation of switching losses

The control strategy of the RCMC is performed on the basis of the Nearest Level Modulation (NLM). Each battery cell forms one voltage level, so that each RBM can provide three levels of voltage, independently on the required voltage polarity of the SM. It is the H-bridge switches configuration, in fact, that determines whether the SM output voltage is negative, positive or equal to zero. Therefore, the number of levels L_v can be written as:

$$L_v = 2N_{cell} + 1 = \frac{2}{3}N_{RBM} + 1 \qquad (1)$$

Where N_{cell} and N_{RBM} are the number of battery cells and RBM per phase, respectively.

Assuming to use Li-Ion battery cells of 4.0V, the phase voltage of the motor considered requires 99 battery cells, divided in 33 RBMs, forming 198 L_v. Fig.4a and Fig.4b show the phase voltage and current waveforms, respectively. The high number of voltage levels guarantees excellent values of THD and a low switching frequency. In fact, the H-bridge switches change their status only when the output voltage polarity needs to be changed.

Using NLM, the maximum switching frequency of RBMs and H-bridge devices is equal to the motor sinusoidal fundamental frequency. Neglecting switching losses can therefore be an acceptable assumption. It has been verified throughout simulation that, for each point of the curve torque-speed, the switching losses result to be the 2% of the total losses at the most.

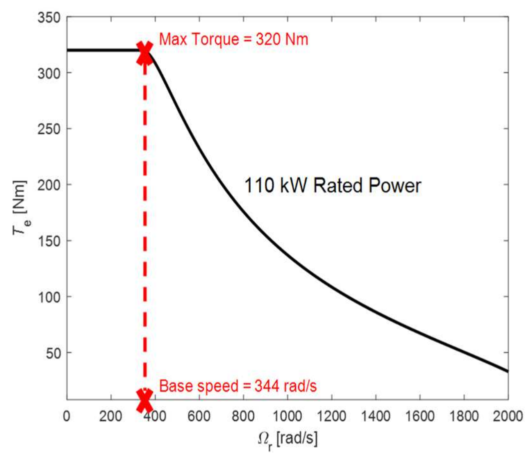


Figure 3 – Torque -speed curve.

TABLE I - MOTOR PARAMETERS

	Value	Unit
Stator Resistance	10	µΩ
Flux constant	0.225	Wb
Pole pairs	4	
Inductance (L_d= L_q)	757	µH
Max Torque	320	Nm
Max phase current peak	237	A
Max phase voltage peak	396	V
Max speed	1500	rad/s

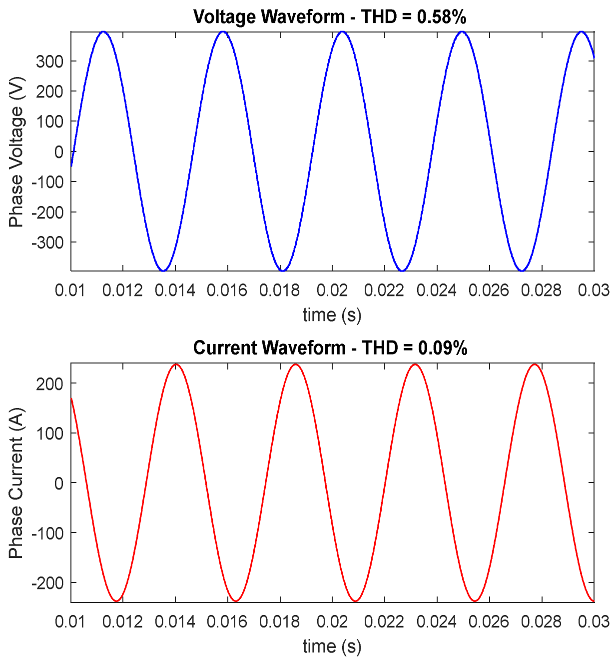


Figure 4 – (a) Voltage waveform and (b) current waveform. The simulation parameters are Torque=320 Nm and w=344 rad/s.

B. Estimation of conduction losses and SM optimization

The total conduction losses per submodule of the RCMC are the sum of the H-bridge and the RBMs contributions. The H-bridge losses can be written as:

$$P_{lossesHB} = R_{dson} I_{rms}^2 (2\ N_{sm}) \qquad (2)$$

Where R_{dson} is the internal H-Bridge MOSFET resistance, I_{rms} is the rms value of the load current, 2 is the number of switches always in conduction and N_{sm} is the number of submodules per phase.

The evaluation of the conduction losses for the RBMs cannot be performed by an analytical expression as in (2), because they are strictly dependent by the instantaneous operative conditions. Fig. 5 shows the trend of the switches in conduction, and therefore of the equivalent resistance, of the RBMs on half period of output fundamental frequency assuming all battery cells are inserted consecutively.

Hence, the conduction losses for the RBMs are obtained by calculating the instantaneous voltage, current and power factor values and the relative RBMs equivalent resistance on one period of output fundamental frequency. The sum of the instantaneous conduction losses is then averaged on the period.

Different criteria can be adopted to design the modular structure of the RCMC, such as energy density optimization, discharging algorithms flexibility, etc . In the following, the optimal combination of the number of RBMs per SM and number of SMs per phase will be found with the objective of minimizing the total conduction losses. According to the modular structure of the RCMC, the optimization may proceed in two different directions:

i. The first option could be maximizing the number of RBMs per submodule. On the other hand, a large number of RBMs connected in series would lead to the necessity of bypassing any of them until the voltage requested is equal to the submodule rating voltage. In terms of conduction losses, three switches are turned on when one RBM must be bypassed. Moreover, the voltage ratings of power switches used for the H-bridge in one submodule is dependent on the number of RBMs connected in series: in general, the higher is the voltage rating, the larger is the internal resistance of the MOSFETs.

ii. The second option could be maximizing the number of submodules. On the other hand, increasing the number of submodule, in order to choose MOSFETs with lower R_{dson}, means increasing the overall number of switches involved in the converter construction. In addition, since two switches of the H-bridge are always in conduction, whether the RBMs are in conduction or not, it is important to define a break-point between the total number of submodule, the MOSFETs R_{dson} and the maximum number of switches acceptable for the converter architecture.

Because of the non-linearity on the RBMs conduction losses evaluation, it is not possible to directly estimate the impact of the two alternatives discussed above. Therefore, an efficiency analysis has been carried out considering four different architectures of the RCMC. For a given voltage rating, MOSFETs with the lowest R_{dson} have been selected. Table II summarizes the structure, voltage ratings and the MOSFETs R_{dson} for the four architectures analyzed.

Fig. 6 shows four efficiency maps, one for each architecture considered. Fig. 6a and Fig.6b present the smallest and the largest area with 99% and 97% of efficiency, respectively. Even if the number of H-bridge is limited compared to the architectures C and D, the MOSFETs R_{dson} affects in significant way the conduction losses. Contrarily, Fig. 6c and 6d illustrate the largest 99% and 98% efficiency area. Both architectures, indeed, have a MOSFETs R_{dson} at least one order of magnitude smaller than the previous cases. Between the two architectures, architecture C is clearly the

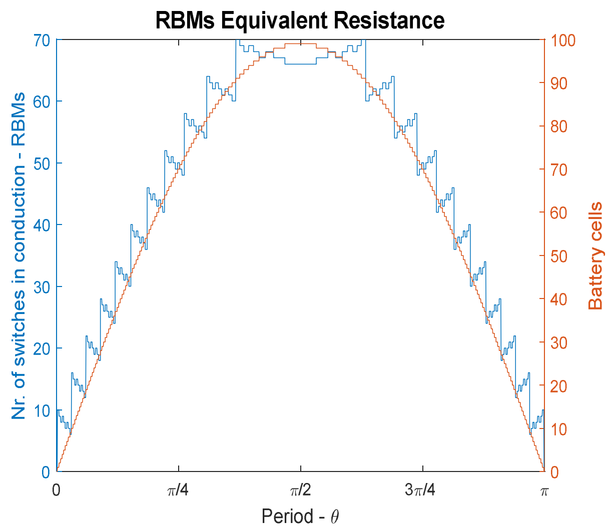


Figure 5 – Trend of the RBMs total resistance compared with the battery cells insertion.

most efficient. Although the H-bridge of the architecture D considers MOSFETs with the smallest R_{dson}, the high number of RBMs connected in series per submodule leads to the necessity of bypassing a substantial number of battery cells during the operation, increasing the overall conduction losses.
In the end, the architecture C results to be the best in terms of efficiency; hence, it will be used as reference configuration for the next sections.

IV. EFFICIENCY COMPARISON WITH CONVENTIONAL IGBT INVERTER

The efficiency analysis is carried out comparing an IGBT inverter and the RCMC converter used to power the three-phase motor, presented above.
Assuming to use Li-Ion battery cells of 4.0V, the two topologies power their load with the following Li – Ion battery systems:

- The IGBT inverter has a traditional battery pack of 396 V.
- The RCMC has 396V connected to each phase terminal of the motor, structured in 11 SMs with 3 RBMs connected in series.

A. Losses modelling

Losses modelling and evaluation are computed in PLECS. The IGBT module FS820R08A6P2B, from Infineon, has been considered. The losses model is evaluated according to [11].
The RCMC is simulated with two different switches. Each RBM is implemented with IPT004N03LATMA1 from Infineon; the switches chosen for the H-bridge are NTMTS0D7N06CLTXG from ON Semiconductor. Their losses models are evaluated according to [12]. Each switch has been modelled in PLECS in order to provide a final computation of both conduction and switching losses.

TABLE II – ARCHITECTURES UNDER ANALYSIS

Architecture parameters							
Architecture	***Nr. of RBMs***	***Nr. of SBs***	***Max. voltage per SB[V]***	***Voltage ratings [V]***		***MOSFETs R_{dson} [mΩ]***	
				H-Bridge	***RBM***	***H-Bridge***	***RBM***
A	33	1	396	600	30	7.5	0.4
B	11	3	132	250	30	4.1	0.4
C	3	11	36	60	30	0.680	0.4
D	1	33	12	30	30	0.4	0.4

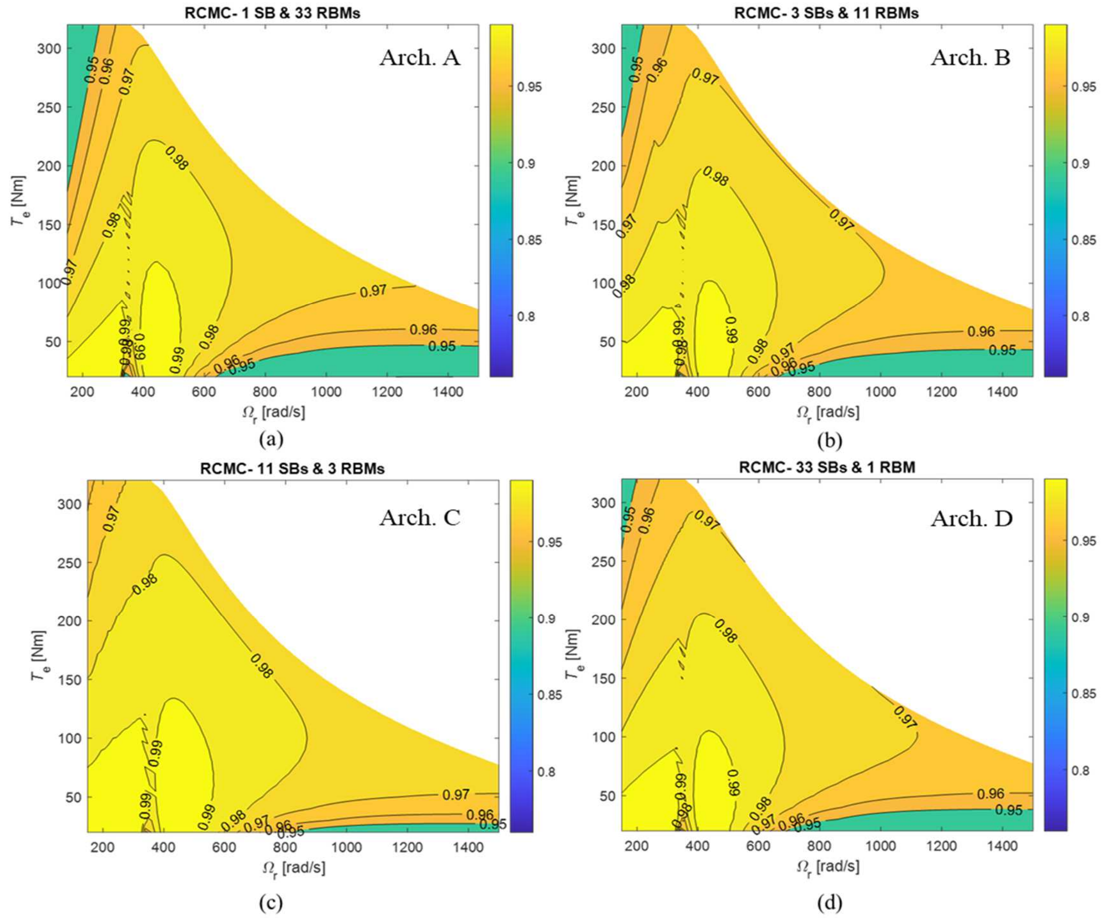


Figure 6 – Efficiency map for four RCMC architectures. (a) 1 Submodule and 33 RBMs. (a) 3 Submodules and 11 RBMs. (c) 11 Submodules and 3 RBMs. (d) 33 Submodules and 1 RBM.

B. *Results and discussion*

The efficiency maps of the RCMC and the IGBT inverter are generated in Fig. 7 for comparison. While the IGBT inverter has higher efficiency values for full load operative points, the performance is deteriorated in partial load condition. Contrarily, the RCMC shows better efficiency ranges in low power operative conditions, still preserving a comparable performance in full load points, with only 1% efficiency reduction compared to the IGBT inverter. The utilization of unipolar switches – MOSFETs behave like a resistor in conduction phase - and the modular structure, which allows to bypass entire submodules when not required, permit to reduce drastically the overall power losses, even in partial load coordinates.

Finally, the new topology guarantees comparable efficiency performance with the state of the art, allowing a better use and saving for the battery cells and the power electronic involved.

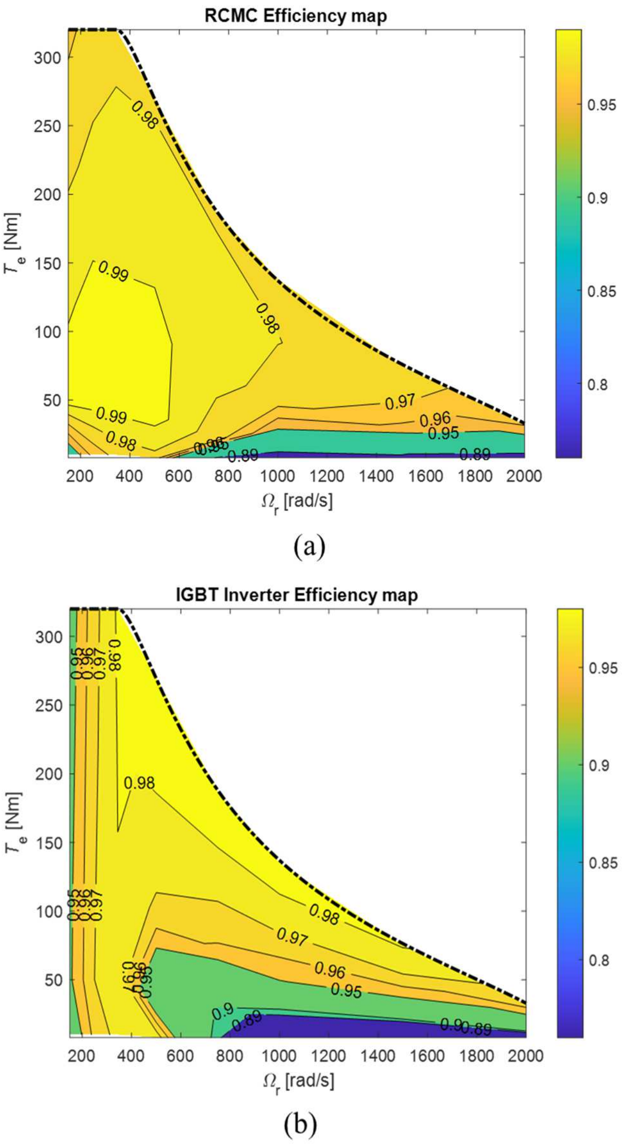


Figure 7 - Comparison of the simulated efficiency maps. (a) Simulated efficiency map of the RCMC. (b) Simulated efficiency map of the IGBT inverter.

V. Efficiency analysis for WLTP cycle class 3

The RCMC has been tested also for WLTP driving cycles. The vehicle model parameters used to calculate equivalent torque and speed for WLTP cycle class 3 are shown in Table III, according to [13].

Fig. 8 shows the position of the WLTP torque-speed operational points on the RCMC efficiency map. The efficiency varies between 99% and 98% for low power operative points, while the performance shows a small deterioration for high peaks of torque and speed. The minimum value of efficiency is 97%.

The average efficiency on each WLTP cycle class 3 has been calculated for both the RCMC and IGBT inverter. Each operative point of the driving cycle has been simulated, evaluating conduction and switching losses. Finally, the RCMC topology results to be significantly more efficient in each cycle than the IGBT inverter. As it is shown in Fig.8, the operative torque-speed points of the driving cycles are placed on the low power area of the mechanical curve.

The efficiency values are shown in Table IV.

TABLE III – Vehicle Model parameters

	Value	Unit
Vehicle mass	1500	kg
Frontal area	1.5	m^2
Drag coefficient	0.28	m^2
Rolling resistance	0.007	
Wheel radius	0.316	m
Gear box ratio	11	
Gear box efficiency	0.95	%

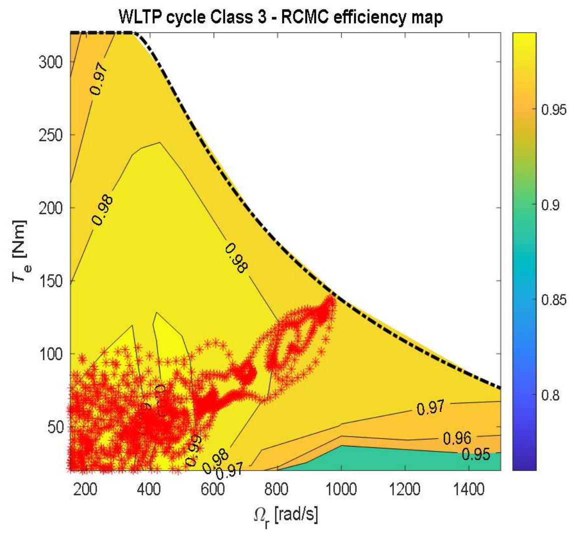


Figure 8 – Efficiency plot with WLTP cycle class 3 torque-speed points.

TABLE IV– AVERAGE EFFICIENCY ON WLTP CYCLE CLASS 3

CONVERTER	WLTP CYCLES CLASS 3			
	LOW	MEDIUM	HIGH	EXTRA-HIGH
RCMC	0.9931	0.9931	0.9931	0.9930
IGBT INVERTER	0.9617	0.9625	0.9627	0.9637

VI. CONCLUSION

A new topology for BEV drivetrain is presented and discussed in this paper. The introduction of RBMs to integrate the battery cells within the power converter and the modular structure of the RCMC allows to flexibly customize the topology in order to best fit the application requirements. In this regard, an efficiency analysis is carried out to evaluate the more performant RCMC configuration to minimize the total conduction losses. Besides, the proposed RCMC efficiency is compared to that of a conventional three-phase IGBTs inverter based on the mechanical characteristic of a typical traction electric motor, also employing the standard WLTP cycle class 3.

This paper clearly demonstrates that the proposed RCMC topology is completely feasible efficiency-wise, and, contrarily to other multilevel topologies, the increased complexity of the structure does not lead to any performance degradation.
Once the competitivity of the RCMC topology in terms of efficiency is established, the main benefit still remains the possibility to fully control each single battery cell during the discharging and charging phases, without recourse to external auxiliary circuits. Future work will focus on possible control strategies during the motoring phase to guarantee the continuous balance among the battery cells, with neither passive nor active BMS required. Furthermore, charging algorithms will be also investigated. The results presented clearly show the potential benefits of next-generation powertrain paradigm, in which the functionalities of both power electric and BMS will be merged in a single structure.

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